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EUROPEAN RESEARCH PROGRAMME ON HYPERSONIC AERODYNAMICS

Eurohyp Review 1976

by

General Editor

S. C. Metcalf

Editors

G. Winterfeld

L. C. Squire

S. C. Metcalf

July 1977

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SUMMARY

This Memorandum reviews the recently completed and current work programme on various aspects of hypersonic aerodynamics research being conducted in European research institutes. Three main areas have been covered, lifting bodies, propulsion aerodynamics, and real gas effects. In each of these sections all jobs have been listed in specialised sub-sections to form a rapidly addressed index. Additionally, there is a brief description or comment on each job, together with references to published papers etc, and an up-to-date address for each contributer.

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INTRODUCTION

This report presents the latest review of research in Europe on all aspects of hypersonic flight; it thus replaces the previous review published in 1973 as RAE Technical Memorandum Aero 1438. Although the interval between these two reviews has been significantly longer than forecast in the last report, this is consistent with the general view expressed in consultations with representatives of most of the European institutes involved in this area of research.

For consistency and ease of use, we have followed the layout and classification of the previous report, even though this means recording a nil return in some subsections. There are thus three main fields of activity in this report, each edited by a different specialist:

Field 1	Lifting bodies	- Dr L.C. Squire, Cambridge University
Field 2	Propulsion aerodynamics	- G. Winterfeld, DFVLR Porz-Wahn
Field 3	Flow of real gases	- S.C. Metcalf, RAE Farnborough.

The information contained in this report is based on replies given to survey cards sent to almost 80 research institutes throughout Europe. This is a significantly wider search than was undertaken for the last review, and it is hoped now includes all institutes who are still active in this area. In fact the present report includes 42 entries from 20 institutes in Field 1, 29 entries from 19 institutes in Field 2 and 65 entries from 29 institutes for Field 3.

The report contains a listing of all current and recently completed jobs in each major Field, classified into specialised subdivisions, giving the job title as well as the name of the institute and persons undertaking the research. Another section provides a description and comment on each job prepared by the specialist editor, and a list of published papers related to each job. In order to make the report as up-to-date as possible, we have also included a brief report and a list of papers presented at relevant Euromech meetings held since the publication of the last report, together with a list of papers presented by Europeans at the International Rarefied Gas Dynamics Symposium held in Colorado in July 1976. Finally, a full list of addresses is given for all the European institutes contributing to this report.

Several of the jobs included in this review were not specifically aimed at hypersonics, but have been included because they nevertheless form essential tools to those devoted to the subject.

The Editors would like to emphasise that this Review is only based on replies volunteered by correspondence and despite their intention to make this a complete Review there will certainly be people and Institutes whose work they have not reported. Furthermore, correspondents may have selected differing classifications for similar work. This particularly applies to work concerned with projects not specifically aimed at hypersonic aerodynamics or propulsion. Such omissions and mis-categorisation may distort the overall picture of current effort on any particular topic.

The main task undertaken in this report is in improving the knowledge of, and communication between, European research workers and Institutes, and their objectives and achievements, in hypersonics. Clearly, there are gaps, and some duplication, in the work described in this report. The Editors have refrained from extensive comment on this aspect since it must be acknowledged that there is not at this stage a unified European research programme.

Overall, it is hoped that this report will form a useful reference for all those already engaged, or contemplating new work, in hypersonics or related fields. The number of people engaged in this activity in Europe has significantly contracted over the past few years and it is, perhaps, even more vital to avoid unnecessary duplication and to encourage more collaboration within Europe. Since there is no formal organisation devoted to this end in Europe it is hoped that Eurohyp, through the present report, can make a real contribution.

COMMENTS OF CURRENT WORK

FIELD 1 LIFTING BODIES - Editor: L.C. Squire

A total of 42 jobs were reported this year, 24 of these are continuations of work reported in the last review, and 18 are new work. All current jobs are listed at the end of these comments with the new work starred. Twenty-five jobs have been deleted from the list in the last report; most of these jobs were reported as complete and a number are mentioned below, and any final reports are included in the references.

11 BODIES DESIGNED FROM KNOWN FLOW FIELDS

111 Design methods

No work on this topic was reported.

112 Theory of off-design

Ganzer and Hoder (ILR) have developed methods for the calculation of the flow around the lower surface of a caret wing at 'off-design'. For the case of the attached shock the method is exact and a computer program is available[1]. For waveriders with subsonic leading edges the flow field is calculated by a numerical method based on slender-body theory[2]. The flow potential for the two-dimensional flow in cross-section planes is solved by source and vortex distributions on the body surface. The Mach number effect on the potential is found from the complete linearised equation for the equivalent body of revolution. The method can be used to find complete pressure distributions and hence overall forces on low aspect ratio bodies. So far results have been obtained on Nonweiler wings and the method is now being applied to waveriders based on cone fields.

At USoAA, Hui's previously reported method for the calculation of the flow past conical wings of arbitrary shape has been published[3]. Also his unified method for calculating the supersonic/hypersonic flow past flat delta wings has been extended to deal with delta wings oscillating about a pitch axis. Different perturbation methods are required for the outer conically hyperbolic and the inner elliptic flow regions. Calculations have been made for oscillations about a general pitching axis for delta wings with attached shock waves. Theoretical predictions of the aerodynamic stiffness and damping have been obtained[4].

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113 Experimental work

Ganzer (ILR) has completed the pressure measurements on the surface of a Nonweiler wing at Mach numbers of 2 and 2.5 at various angles of incidence. At ICL pressure distributions have been measured on a series of waverider wings based on a 28° wedge with $s/l = 0.267$. The tests were made at $M = 22$ and the lowest Reynolds number based on the wing chord was 3600. Heat transfer distributions have been measured at corresponding conditions. Two techniques were used. In one, thin nickel shell models with thermocouples were injected into the flow and heat flux measurements obtained at a number of points on the pressure side of the wings. In the other method a transient heating technique was again used but with the loaded resin model coated with thermally sensitive phase-change paint. Together the two techniques have yielded accurate and detailed heat transfer distributions[5].

At TUBS the work started by Kipke on the measurement of pitot pressures on the leeside of waveriders at Mach numbers between 10 and 15 is complete and a final report is in preparation.

114 General

12 FLOW ABOUT BODIES OF GIVEN SHAPE

121 Axisymmetric bodies

Theory

Trass (NLR) has developed a numerical method for calculating the steady inviscid flow about blunt axisymmetric bodies at incidence[6]. The program uses a Lax-Wendroff difference scheme marching in the general flow direction and the bow shock is determined by the shock-capturing technique. The subsonic flow at the nose is computed by means of a separate program. The method has been compared with an accurate (but time-consuming) program which uses the shock fitting technique. The present method is very suitable for engineering work whereas the accurate method requires too much computer time.

Experimental work

An extensive programme of work on the flow over axisymmetric blunt bodies with concave conical forebodies has started at VKI[7-9]. This study concerns flows over a family of concave conic shapes developed on turbulent ablating nose regions of re-entry vehicles. For small amounts of concavity, it is shown that a system of two shock waves was developed with high values of pressure and heat transfer produced downstream of their intersection. A simplified analysis of the

flow field has been made. For large concavity the flow becomes unsteady, forming the pulsating and oscillating behaviour seen earlier on spiked blunt bodies. In order to provide further understanding of this unstable flow, a detailed study of the flow over spiked cone models in supersonic and hypersonic flow has started.

In new work at OXU, Schultz is using free-flight methods to determine normal and axial force coefficients and centres of pressure. Representative hemispherical-cylinder flare combination models have been tested, made neutrally stable by adjustment of the centre of gravity. Multi-spark schlieren photography gives up to 11 model locations during the duration of the flow in the gun tunnel. The test conditions are $M = 7.2$, Reynolds number 7.9×10^7 per metre and the total temperature is 700 K.

At FAA, Larson has completed the experimental work on wing/body combinations at Mach numbers of 4 and 7. The results are being compared with theoretical results based on a panel method, on slender-body theory and on a method using a generalised interference load distribution on the body[10].

A reflected shock tunnel at RAE (F) has been extensively modified to allow routine operation at high Reynolds numbers[11]. The modifications include increased gas storage, greater pumping capacity, contoured nozzle for $M = 9$ and isolation of the test section by mechanical means. Work in the tunnel is confined to heat transfer measurements on axisymmetric re-entry bodies.

Two items of work on bodies of revolution in rarefied hypersonic flow have been reported. At DFVLR (G), the drag of cones at zero incidence has been measured in the near molecule regime for different cone angles and different gases. In particular the drag variation with wall temperature has been studied[12]. Stanton number and recovery factors have also been found in the same conditions. The drag measurements have been compared with a near-free molecule theory and some information obtained about gas surface interaction phenomena using different gases such as helium, argon and air. At DFVLR (PWG), rotational temperature measurements have been made on the stagnation line of a hemisphere[13]. Serious problems due to strong self-radiation have been overcome. To overcome the rapid broadening of the spectrum with increasing temperature connected with a marked reduction in the individual line intensities a new method is used. This uses the P-branch intensities for rotational temperature determination. Measurements of the vibrational temperatures have started.

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122 General shapes

Theory

A locally two-dimensional finite difference method has been developed by Walkden (USaCC) for the calculation of steady three-dimensional supersonic flow. The numerical technique, which is extremely stable, has been used successfully to compute the following flow fields: (a) a swept delta wing with round subsonic edges at zero incidence, (b) a simple step intake, (c) a fuselage/cockpit canopy combination, and (d) a variety of conical body shapes.

At TUD, Hendricks has calculated the shapes of the domains of influence and of dependence in expanding supersonic flow[14]. This knowledge is the basis of an investigation of the reliability of two current sonic boom theories[15]. A procedure has also been developed for the calculation of the flow in three-dimensional expansion regions including the flow on the leeward side of trapezoidal and delta wings[16]. Work in this topic continues with particular reference to the mathematical foundations of the calculation procedure; its relation to the method of strained coordinates and the convergence of successive higher approximations to the exact solution.

Also at TUD, Bannink and Bakker have made local investigations of the flow near conical stagnation points on a cone at incidence. This work uses linear theory and it is intended to extend the work using the exact equations[17]. Attention may also be given to flattered cones to study the generation of vortices. In conjunction with this work an experimental study has been made of the complete flow field around a 7.5 semi-angle cone at $M = 3$ in the incidence range $30^{o} < \alpha < 75^{o}$ [18,19].

Experimental work

At CIT, Stollery and Richards have made a detailed survey of a delta wing of 70^{o} sweep at $M = 2.5$. The measurements include upper and lower surface pressure distributions, schlieren and vapour screen photographs and surface oil-flow patterns. The results have been compared with thin-shock-layer theory and other predictions[20,21]. They have also designed a new open-jet test section for the hypersonic helium tunnel. The initial programme consists of the evaluation of an 'afterglow' technique for flow visualisation followed by the study of the flow around simple shapes using this technique.

Allegre (CNRS) has just started an investigation of the flow due to sudden changes of incidence of a flat plate, he is also looking at the effect of sudden changes in trailing edge flap angle. These tests are being made at $M = 8$ at a Reynolds number of 2200/cm.

At UCED, Squire has continued a study of the flow over delta wings at supersonic and hypersonic speeds. Earlier work on the effect of recessed lower surfaces has been published[22]. A possible connection between a change in the flow pattern on the lower surface and the change from leading-edge separation to attached flow on the upper surface has been found[23]. Further work on this topic is in progress.

At DFVLR (PWG), Schwartz has restarted work on uniformly valid thin-shock-layer theory for three-dimensional hypersonic flow. While Pike at RAE (B) has continued his work on the calculation of forces on general bodies using Newtonian theory[24].

Bisch (CNRS) has started theoretical and experimental work on the drag reduction of a sharp flat plate in hypersonic rarefied flow by means of changes in the leading edge shape[25].

Yegna Narayan (UCED) has completed an experimental study[26-28] of the flow over three wings with curved leading edges at Mach numbers of 2.5, 3.5 and 4.5. Complete pressure distributions and shock shapes have been obtained for a range of incidence and yaw. He has also made a simple extension to thin-shock-layer theory and in general the results from this extension are in excellent agreement with the experimental measurements. In the case of the wing with an attached shock over part of the leading edge near the apex it is found that the flow over the whole wing is dominated by the apex flow.

At ILR Szodruch is making an experimental study of the flow over delta wings with various cross-sections[29]. The Mach number varies from 2 to 4 and the models are tested over an incidence range up to 30°. At all Mach numbers the pressure on the upper surface starts to rise as the incidence is increased through an incidence of about 12 to 18°. Oil flow patterns and schlieren show that this effect is associated with the bursting of the vortices above the wing, while the embedded shocks move towards the leading edge. Wedges positioned near the trailing edge of the wings trigger the vortex bursting. An attempt has been made to predict the flow field. The model is based on conical flow and consists of a detached shock wave, an expansion over the boundary layer, an embedded shock and a separated boundary layer forming the spiral vortex.

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Richards (VKI) has made a number of studies of the flow over wing-body combinations similar to tactical missiles. The tests are made at subsonic, transonic and supersonic speeds. At DFVLR (PWG), Wyborny is measuring six force components in free-flight tests in a gun tunnel[30-32]. Various optical and electronic parts have been made to minimise size and weight. (The latest model had a length of 53 mm, a diameter of 25 mm and a mass of 41.5 g.) Tests have been made for a series of axisymmetric models and results for a number of incidences can be obtained in one tunnel run.

Lundgren (FFA) has measured pressure distributions and heat transfer in a hypersonic tunnel on a delta wing with blunt leading edges. The model, which was built and instrumented by RAE (F), has also been tested in a free-flight experiment at Woomera, Australia. In the tunnel tests the effects of small angles of incidence and yaw have been studied. Only small, but still significant, variations in pressure and heat transfer have been observed so far[33].

Koppenwallner (DFVLR (PWG)) has completed his work on the aerodynamics of typical re-entry vehicles[34].

13 INTERFERENCE PROBLEMS

131 Corner flows

Strömsdörfer and Mollenstädt (TUBS) are making a full study of the flow in corners at hypersonic speeds. In the first part of the investigation pitot-pressures in the flow field, wall static pressures and heat transfer have been measured in corners with unswept leading edges. These investigations show a very complicated shock system. A main feature of the flow is a pair of vortices originating from the leading edges causing very strong peak heating rates. This effect increases with decreasing corner angle, for example, with a corner angle of 60° the peak heating rate is 14 times as great as that in two-dimensional flow[35]. The work is to be extended to study the effect of swept leading edges in the Mach number range from 10 to 16. These tests will cover a range of sweep angles, corner angles and wedge angles and the measurements will be similar to those made for the unswept edges. Similar tests have been made at DFVLR (PWG).

132 Intersections and interacting bodies

This work at ICL extends previous experiments on two-dimensional (flat plate) and axisymmetric separations at compression corners to the

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three-dimensional case. The approach is to develop an axisymmetric turbulent boundary layer on a cone-cylinder forebody at zero incidence ($M_\infty = 9.0$, $Re_\infty < 5.0 \times 10^5$/cm; a three-dimensional separation is subsequently generated by careful orientation of a conical flare afterbody. It is hoped to isolate two main effects by this means: (a) the case where the dominant influence is a large pressure gradient around the flare circumference, generated by inclining the flare axis to that of the cylinder, (b) the effect of yawing the separation line, whilst maintaining a low circumferential pressure gradient, by simply off-setting the flare axis parallel to that of the cylinder.

Basic schlieren and pressure surveys are now nearly completed. Measurements cover separation, plateau and reattachment regions and appear to justify the original selection of flare geometries, although it is not completely possible to isolate the two main effects. There is good agreement with free interaction correlations in the region of initial pressure rise, although the incipient separation angle depends on the particular crossflow condition. Future work will include heat transfer measurements and surface flow visualisation and a more detailed investigation of the boundary layer state prior to separation.

14 CONTROLS AND DYNAMICS

141 Aerodynamic controls

Wyborny (DFVLR (PWG)) has made three component measurements at $M \doteq 8.8$ on different missile-configurations having different nose shapes, different deflected spikes and cross wings. The nose shapes were chosen by means of estimates based on Newtonian theory[36].

At VKI, Ginoux[37] is concerned with an experimental and theoretical study of two-dimensional laminar boundary layer/shock wave interactions on configurations consisting of flat plates equipped with deflected convex ramps. The ramps have the form of circular arcs. Work on this project has been split into three major sections. These are briefly described below.

Interface static pressure distributions were measured throughout adiabatic laminar boundary layer interactions generated by a convex deflected flap on a flat plate and by an oblique shock impinging at the hinge line of a flat plate/convex afterbody. In the latter case the angle at the hinge line was zero. The tests were made at a free-stream Mach number of 2.21 in the VKI facility S-1. These tests were made in order to confirm that the equivalence between

interactions generated by flat ramps and by incident shocks on flat plates which is inherent in theoretical integral methods could be extended to configurations with convex curvature. Experimentally the equivalence was confirmed and successful comparisons made between the measured pressure distributions and those predicted by the integral method modified to include streamwise curvature. This work is reported in the above reference.

The above experimental work has been extended to the higher Mach number of 5.55 using the VKI facility H-3. Pressure distributions have been measured throughout interactions generated by convex ramps for a range of free-stream Reynolds numbers under adiabatic, moderately cooled and highly cooled wall conditions. Both laminar and transitional data have been obtained. For the adiabatic laminar interaction data satisfactory comparisons have been made with theory. At the same time a theoretical parametric study has been made of the effect of variable ramp radius on the characteristics of two-dimensional adiabatic laminar interactions. This work was published by VKI early in 1976.

It is proposed to perform a further series of tests to measure heat transfer rate distributions at M = 5.55 under the same conditions as for the pressure measurements described above. In hand with this the energy equation will be included in the computer program such that heat transfer rates can be predicted theoretically. It is hoped that the measured pressure and heat transfer rate distributions will provide useful data concerning a number of anomalies associated with peak heating correlations.

Hefer (DFVLR (G)) has made an experimental study of the aerodynamic interference induced by a supersonic jet exhausting perpendicularly from a flat plate into a hypersonic rarefied gas flow. Jets of helium, argon and nitrogen injected into a main stream of air[38]. The flow field has been investigated by measuring pitot pressures, flow directions and gas concentrations. The interact force has been found from the measured wall pressures.

142 Stability and control problems

At USoAA, East[39,40] has continued his work on the stability and control problems of wedges and delta wings. Since the previous report, additional work has been carried out in an attempt to resolve previously reported anomalous aerodynamic stiffness measurements. Half model delta wings have been tested using flexure-supported models and a moving reflection plate. The additional

pivot stiffness gives more cycles of oscillatory motion for analysis and measurements of both aerodynamic stiffness and damping have been obtained. Stiffness derivatives for a single wing were found to be consistent with theoretical predictions, in contradiction to results obtained using the double wing system used earlier. It now appears that a dynamic interference between the two wings is a possible explanation.

The accuracy of the damping measurements for delta wings oscillating in the hypersonic gun tunnel flow is limited due to various forms of unsteadiness. However, the measurements appear to give higher values of aerodynamic damping than theoretical predictions.

No further work is contemplated in the gun tunnel. Future work will be performed in a light piston isentropic compression facility recently completed, which is designed to reduce the level of the reservoir pressure fluctuations.

Also at USoAA, a theoretical and experimental programme has commenced aimed at the prediction of the stability derivatives of various axisymmetric bodies with particular emphasis on the effect of nose bluntness.

Two aspects of the theoretical programme are in progress. The first employs an extension of the approximate shock/expansion method to conical bodies with slight nose bluntness; the effect of nose bluntness being included by using the blast wave analogy. Although the empirical nature of this method is appreciated, analytical expressions for the derivatives permit a wide range of angles and bluntness to be considered.

The second method is based on a numerical perturbation of a time-dependent steady flow computer calculation for a blunt cone/cylindrical afterbody shape. The steady flow part of the calculation has been successfully completed for the forebody but difficulties have been experienced on the afterbody. Work is continuing with alternative methods for the afterbody steady flow, after which the unsteady perturbation will be attempted.

Experimental work has been concerned with the adaptation of the gas bearing pivot and half-model oscillatory techniques reported in item 142.1 to measurements of the damping derivatives of a series of axisymmetric shapes having a blunted conical forebody as a common characteristic. Following the problems encountered with flow unsteadiness in the hypersonic gun tunnel, the experiments await the completion of a new steady flow high Mach number facility. The facility is based on the light piston isentropic compression system proposed by Jones *et al*

of Oxford University. A level of reservoir pressure fluctuation of about 1% and running times of 0.35 second should permit more accurate dynamic derivative measurements than have been possible hitherto.

A number of new developments have started at ARA. Morton has produced a novel technique to enable the M = 7 tunnel to be started with very bluff models installed. The method employs a hemispherical wax fairing which melts in the first few seconds of the test run leaving the bluff model exposed to the started tunnel flow. He has also used the crossed spring flexure dynamic stability rig in the M = 7 blowdown tunnel and in the large transonic tunnel to measure aerodynamic stiffness and damping-in-pitch derivatives of the STA standard 10° cone model and of an axisymmetric hemisphere-cylinder-flare model. The data is being analysed. Also at ARA measurements of lift, drag and pitching moment and pressure distributions have been measured at M = 7 on the standard hypervelocity ballistic model HB-2 and on other flared models.

Ganzer (ILR) has tested a hypersonic aircraft model based on a cone flow waverider at Mach numbers from 0.3 to 3.0. The leading edges are subsonic at all speeds and the studies include three component force measurements, pressure distributions, and shock and vortex positions. Stability and control was studied by using different flap and ailerons at the trailing edge.

Finally Hindelang (HBN) has used Newtonian theory to calculate aerodynamic coefficients and stability derivatives at hypersonic speeds on the Apollo-Command module[41].

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FIELD 2 PROPULSION AERODYNAMICS - Editor: G. Winterfeld

General remarks

The present survey has shown that in the past three years the decline of research work in the field of hypersonic propulsion has continued. This is so especially for the more applied work. The work reported here is more or less of basic nature. In the field of combustion and injection a strong tendency to relate work to gas turbine combustors can be observed. Therefore, in several cases included there is only a weak relation of the work done to hypersonic propulsion.

21 THEORY OF FLOW WITH HEAT ADDITION

No further work has been done by Broadbent at RAE (F); the last results are summarized in Ref 1. A review of the whole subject is intended in Progress of Aeronautical Sciences. The latest results were for two-dimensional flow suitable for a caret-wing, comprising a two- or three-shock intake followed by a ducted region of heat addition and a nozzle. The free-stream Mach number was 7.5. Propulsive efficiencies of over 0.65 were calculated at C_L up to 0.084 and C_{DP} (net wave drag coefficient) of about -0.06.

211 Heat addition over finite regions

22 FLOWS WITH HEAT ADDITION - EXPERIMENTAL

221 Diffusion flames

The work on diffusion flame stability, carried out by J.F. Clarke[2-5] at Cranfield Institute of Technology (CIT), is continued with emphasis on good numerical accuracy for both steady-state and perturbed fields, especially in respect of chemistry in the H_2O_2 mixture. Parameter perturbation schemes are being used to provide analytical results wherever it is possible. Work on supersonic flow with embedded deflagrations is terminated; a final report is in preparation.

At the Technological University of Stuttgart (UoSIT) non-equilibrium turbulent diffusion flames of boundary layer type are being numerically analyzed by J. Algermissen. Complex finite-rate chemistry models are used for the combustion. Analyses are being carried out for H_2O_2, H_2-air and methane-air systems.

Work on mixing and combustion with transverse injection of fuel gas into hot supersonic airstreams of Mach numbers 1.5 to 3 is continued by J.P. Baselt[6] and Bier, Technological University of Karlsruhe (TUKT). Ignition conditions and

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propagation of mixing and combustion have been investigated for hydrogen and methane injected into a supersonic stream of 10 mm diameter, heated by an arc heater (350 kW), static temperatures 800-2000 K, pressures 0.2-1 bar.

At DFVLR (B) work on heat addition by combustion of pyrophoric fuels (TEA) was continued by Kallergis and Ahlswede[7,8]. The ignition delay as well as the Al_2O_3 deposits on a lifting propulsive body model at low velocities first are experimentally determined. A study was made on the heat input into a cylindrical combustor burning aluminium trialkyls, considering the kind of fuel and the fuel mass flow. Pressure-velocity-diagram lines of constant air-fuel-ratios are plotted. The activities were stopped in 1974.

Studies on turbulence in diffusion flames are carried on by K.N.C. Bray, University of Southampton (UoSAA)[9,10]. Time-resolved optical measurements in turbulent flames are being made using a variety of techniques including laser-Doppler anemometry, crossed-beam correlation and spectroscopic methods. Fluctuation intensities, spectra, scales and correlations are obtained in laboratory flames. Theoretical modelling studies, emphasising the interactive effects of turbulent fluctuations and heat release in flames are continuing.

222 Supersonic combustion with shock waves

Theoretical and experimental investigations of shock-induced combustion of hydrogen in a supersonic stream are carried out by J. Algermissen, Technological University of Stuttgart (UoSIT), using a free-jet test facility and ultizing interferometric, mass-spectroscopic, infra red and Raman-spectroscopic methods. The experiments are expected to give details of the local and time-dependent processes in the mixing and reaction zone. A computer code, based on the methods of characteristics is being developed for numerical analysis of the non-equilibrium flow.

At the University of Göttingen (IPC), theoretical and experimental investigations on flow stability of special turbulent flames connected with shock waves are carried out by H.G. Wagner. The experimental work uses methane-flames[11,12].

223 External heat addition

The DFVLR activities on external combustion in the flow past lifting bodies by Kallergis *et al* [13-17] were carried on at DFVLR (B) until 1974, when this work was stopped too. Investigations about the experimental determination of a hot nitrogen jet and of a nitrogen propane flame at atmospheric pressure using short-time photography are completed. The hot jet descending from

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an arc-heater installed in a lifting-body model is intended to stabilize the supersonic combustion along the lifting body. The above mentioned reports give details on the development of the hot jets.

Work on external heat addition on flat plates and bodies of revolution carried out at DFVLR (PWG) by F. Maurer *et al* up to 1972 is intended to be resumed in 1976.

224 Dual-mode combustion - miscellaneous

Work on flame holders and turbulence generators for high-velocity launching vehicles has been started in 1975 by T. Valdsoo at the Institute of Technology, Aeronautical Department, Stockholm (ITS).

225 Kinetics of combustion

A new study is initiated by J. Bellet at ENSMA, Poitiers; it aims at new data about the combustion in the primary zone of combustors. The object is to determine the variations of reaction rates (versus the degree of completion of the reactions) in the combustion stabilizing by mixing of burnt gases with fresh gas, taking into account the influence of turbulence. The experimental set-up with a $10 \times 10cm^2$ cross-section allows the supply of a quasi-uniform mixture of burnt and fresh gases. The program includes concentration measurements by gas sampling, velocity and flame temperature measurements, and turbulence intensity measurements by laser-Doppler.

23 INJECTION AND MIXING PROBLEMS

231 Wall injection including film cooling

All work on injection from walls into supersonic flow done so far at the Institüt für Luft- und Raumfahrt, Technological University of Berlin by U. Ganzer *et al* (ILR) is cited in two reports[20,21]. The application of the same principle for subsonic mixing problems of combustion products with secondary air in a turbojet combustor has been investigated in a third paper[22]. No further work on mixing problems for wall injection is intended.

H. Rick, Technological University of München, Institüt für Flugantriebe (TUMF) has treated the problem of multiple-jet injection of gaseous fuels into supersonic flow. Injection with minimal loss for the main flow is obtained by several gaseous jets injected laterally into the primary flow. In Ref 23 this method is approximately described by a calculation model, experiments have been carried out in a short-duration test facility.

At Oxford University, Engineering Laboratory (OXU), D.L. Schultz, M.R. Smith and T.V. Jones completed a programme of flat plate, zero pressure gradient film cooling studies for Mach numbers 0.2, 0.5, 0.7 and 1.86 [24].

A subsonic and supersonic reflected shock tunnel was used, with total temperatures 500 K, 1000 K and 2000 K. Studies are related to design of cooling systems for gas turbine vanes and rotor blades. A new free piston isentropic compressor has been constructed with $T_T = 500$ K, $P_T = 7$ bar, flow duration 0.2-0.4 s for cascade testing of film cooled blades[25].

232 Coaxial injection

At ILR, Technological University of Berlin, J. Szodruch and H. Holder investigate the interaction between a sonic or a supersonic jet directed counter to a supersonic stream. The jet issued from the nose of a blunt body generates a system of two curved shocks. Schlieren pictures for different jet Mach numbers and total pressures show the influence on shock shape and displacement[26].

G. Strömsdörfer, Technological University of Braunschweig (TUBS) studies the hypersonic flow past blunt bodies with central air ejection, using the gun-tunnel of Institüt für Strömungsmech. Mach number range $10 < M < 16$, Reynolds number based on model-diameter, and free-stream condition was $6 \times 10^4 < Re < 2.5 \times 10^5$. For the cases of subsonic as well as sonic injection the following investigations were made: static pressure measurements on the nose contour, heat transfer measurements using the transient thin-skin-technique, Schlieren-pictures of shock shape and other flow details. The work is finished and will not be continued[27,28].

M. Fiebig[29,30], Gesamthochschule Duisburg (GHDF) is preparing experiments on supersonic and hypersonic mixing of coaxial jets with streamwise pressure gradient. Preliminary experiments will be performed on a pilot experiment with subsonic-subsonic, subsonic-supersonic mixing of different gases. A numerical programme has been developed to determine the initial mixing profiles from arbitrary initial conditions for given nozzle shapes. These initial profiles will be used to calculate the mixing within the slender channel approximation. Laminar and turbulent mixing will be considered using different turbulence models.

233 Special injection and mixing systems

234 Boundary layer investigations

At the Technological University of Stuttgart, J. Algermissen (UoSIT) is investigating chemically reacting boundary layer flows with the main emphasis on determining the importance of finite-rate chemistry in accurately predicting the

non-equilibrium boundary layer properties. Boundary layers under investigation include hypersonic air boundary layers on catalytic and non-catalytic walls as well as turbulent boundary layers with mass addition and combustion.

Harvey, Hillier, Bartlett and Edwards at ICL are undertaking a fundamental study of a hypersonic turbulent boundary layer using a gun tunnel. Initially a flat plate model is being used and the time-averaged flow properties tabulated. Measurements include pitot pressure, total temperature, heat transfer, surface static pressure and skin friction. The future development is being concentrated on measuring the time resolved density fluctuations within the layer using an electron beam.

K. Stewartson, S. Brown and P.G. Williams (ULUC) work on hypersonic boundary layers, which is reported in Refs 31 and 32.

Heat transfer measurements in a ramjet inlet are done by S. Lundgren, Aeronautical Research Institute, Bromma, Sweden (FFA). A new heat transfer gauge measuring the average transient heat flow has been developed. Very short testing time is necessary. Best results are achieved if the model is shielded during injection into the wind-tunnel and thereafter suddenly removed. Work was delayed due to capacity shortage but will be finished in 1976.

24 LIFTING PROPULSIVE BODIES

25 EXHAUST PLUMES

At CNRS Meudon, studies on interaction between exhaust plumes and external surfaces in rarefied flow conditions have been performed by Allègre, Lengrand and Raffin. The first part concerned theoretical and experimental studies of the plume itself; presently the investigation of its interaction with external surfaces is beginning.

At RAE (F), heat transfer measurements for a rocket plume impinging on a flat plate are being carried out by J.E.G. Townsend. Tests have been performed in a small vacuum chamber, using active gauges for heat transfer measurements.

N. Bellomo of Istituto Politecnico, Torino (IMR) is working on exhaust plumes. One of his last publications[18,19] deals with nozzle contours for maximum thrust.

251 Theoretical studies

252 Experimental studies

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FIELD 3 FLOW OF REAL GASES - Editor: S.C. Metcalf, RAE

31 HIGH TEMPERATURE PHENOMENA

311 Properties of hot air or component gases

As was pointed out in the last Eurohyp Report, this section relates mainly to increasing our knowledge of relaxation effects, and much of the work has been carried out for non-specific hypersonic flow applications. We must assume that most of the jobs listed in the last report, under this heading, have been concluded since we have received no response concerning progress for the present review.

H. Grönig, now of THARL, has developed a technique for predicting the transport properties[1] of arbitrary complex systems, including diffusion and thermal diffusion. The method is presently being applied to dissociated boundary layers behind moving shock waves. Meanwhile, A.W. Neuberger (DFVLR (PWG)) is developing a calculation method for the composition, electrical conductivity and total radiative source strength of nitrogen plasmas, assumed to be in local thermodynamic equilibrium. The method, when applied at a pressure of one atmosphere, gives values for electrical conductivity and continuum radiative power which are closer to experimental data than those predicted by any other theoretical method. This new method also allows for line radiation to be taken into account when calculating total radiative source strength: the line radiation can be extrapolated with respect to pressure and temperature.

312 Hypersonic equilibrium flows

No jobs have been reported in this category for the present review. Some of the items reported in the last survey have developed to the point where they now appear in later sections of this report. Also, many of the items were concerned with equilibrium boundary layers, these would now be reported to Eurovisc*.

313 Relaxation effects in hypersonic flows

Based on the replies to enquiries for the present review, about one third of the jobs reported in the last Eurohyp report under this heading, are still progressing; another six new jobs have been identified.

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* The latest Eurovisc report, dated September 1976, has just been published by the RAE as Technical Memorandum Aero 1690.

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H. Buggish at THD has produced a new method, based on simplified equations, for studying the propagation of one-dimensional unsteady, or two-dimensional steady waves in a relaxing gas. At present the method is restricted to a gas with one internal degree of freedom, where the relaxation is weak, and where the amplitude of the wave is relatively small. This work has not yet been published. The work of R. Brun (LDSR) previously reported, has continued to be developed. This is concerned with the determination of transport coefficients in non-equilibrium flows using kinetic theory, and has been reported in Refs 2 and 3.

H. Oertel of TUKS reports that his work on the influence of oxygen vibrational and dissociation relaxation on shock reflection has been concluded[4,5]. Data has been obtained behind incident and reflected shock waves in a low pressure shock tube. The experiment revealed that previously assumed rates for oxygen were in error and new reaction rates have been produced[6] by numerical fitting. Theoretical and experimental investigations of oxygen dissociation behind stationary weak oblique shocks have also been concluded at TUKS; again dissociation rate coefficients have been recalculated for this situation and reported in Refs 7 and 8.

At DFVLR (PWG), Schweiger is studying the interaction between the bow shock from the leading edge of a flat plate and the shock generated by a cylinder in the flow field. This job has started since our last review. The rarefaction of the stream is low so that the shocks are thick and in the merged layer, non Rankine-Hugoniot, region. So far profiles of density, rotational and vibrational temperatures have been obtained using an electron beam fluorescence technique (somewhat similar experiments are reported in 344.4). F.J. Hindelang (HBN) reports an investigation of the dissociation rate behind strong normal shock waves using an approximate solution of the Boltzmann equation.

A particularly interesting experiment has been conducted by R.A. East (UoSAA). This involved the heat transfer to catalytic and non-catalytic surfaces at the stagnation point of a Mach 10 flow of dissociated high temperature air[9]. New data has been obtained for surface recombination rates and for the stagnation point heating in a regime where the gas phase reactions in the laminar stagnation point boundary layer are in a non-equilibrium regime. At present there are no plans for further experiments on this topic. B. Schmitt-v-Schubert, DFVLR (D), is also looking at the blunt body[10] in hypersonic flow, but at low Reynolds number where the shock and boundary layer are merged. The effect of vibrational

relaxation is considered for both equilibrium and non-equilibrium free-stream conditions. This study has produced computations for atmospheric flight conditions as well as for the simulation of these in a wind tunnel.

Johannasen's (UMMF) previously reported studies have continued[11,12] with numerical calculations of the supersonic flow of a vibrationally relaxing gas past a slender cone. Particular interest has been taken in the development of the bow shock into a fully dispersed wave at large distances from the body. It appears to be possible to relate these waves to the development of waves in the atmosphere, where vibrational relaxation of oxygen and nitrogen is significant. Work is also in the initial stages of calculating the development of N-waves in a vibrationally relaxing gas, as such knowledge is considered to be an important step towards the understanding of long range propagation of high energy sound waves in the atmosphere.

Another area of interest on which there has been new work is the mixing of non-equilibrium flows. M. Becker (DFVLR (PWG)) used as the primary flow N_2 in a non-equilibrium state through a rapid expansion[13,14]. The secondary flow was of CO_2. The initial experiments, in which measurements were made using gas chromatography, produced inconclusive results and an optical technique is now being evaluated. Another new theoretical and experimental investigation of relaxational phenomena in mixtures of CO_2, N_2 and O_2 is being conducted by G. Adomeit (THAM). The Mach number in the investigation is between 5 and 20. One particular finding is that dissociational relaxation of CO_2 increases with increasing the component N_2 in the initial mixture.

F.J. Hendelang (HBN) has continued his development[15] of numerical techniques for studying relaxation effects. He reports progress on predicting the influence of multiple quantum transitions which has been applied to expansive flows of CO, N_2 etc. Meanwhile, M. Fiebig and N.K. Mitra (DFVLR (PWG) and GHDF) have developed a new method for calculating high temperature nozzle flows for gases and mixtures with internal degrees of freedom[16-19]. The method can be used for arbitrary nozzle shapes and initial boundary conditions. Of particular note is that these workers report that they have overcome the severe numerical difficulties posed at the subsonic-supersonic transition. So far the method has been applied to equilibrium flows with variable specific heats and/or with vibrational non-equilibrium, with good comparison with experiment. An extension to include dissociational non-equilibrium is planned.

At LDSR, R. Brun has been investigating population inversion (vibrational levels) in blast waves[20,21], steady and unsteady expansions, detonations and chemically reacting flows. M. Jischa (UEFM) reports his progress on non-equilibrium boundary layers in Refs 22 to 26. B. Gampert, at the same institute, has been studying chemically reacting boundary layers, details of which can be found in Ref 27.

W. Schönauer (TUKR) reports a very comprehensive computer program has been developed which solves the laminar two-dimensional hypersonic boundary layer equations for chemically reacting non-equilibrium air mixtures (up to five components). Details are available in Eurovisc report item 15.16.

314 Radiation effects in hypersonic flows

No further progress has been reported directly from the three institutes declaring activity in this section of the last report, but reference to other sections, eg 311.1 (Grönig - THARL), indicate that radiation effects are being considered as part of a more general approach to high temperature phenomena.

315 Ablation effects in hypersonic flows

DFVLR (PWG) continue to be the only laboratory reporting specific studies on ablation. K. Kindler has described[28] experiments on CFC and PTFE, and compounds of these materials, in which rate of ablation was continuously monitored in a high energy, high Mach number gas stream. The experimental results are reported to be in good agreement with numerical computations. No European institute has reported interest in non-ablating thermal protection materials, ie radiative loss surfaces as currently being developed for space shuttle.

316 Optics and electrics of hypersonic flows

317 Magnetoaerodynamic phenomena

In the last report there were four entries for section 316 and six items for section 317; there have been no submissions for either section for the present review. This suggests that the following laboratories are no longer active in this area: ONERA, ISL, LRBA, EMI, UPaMT, UPoS, and UMIMF. Clearly, this represents a very significant loss of potential within Europe.

318 Experimental techniques

The previous report contains some 11 entries, most of them related to research on the topics reported above, especially sections 316 and 317. Since

these jobs involved most of the laboratories listed in the preceding section, it follows that a cut-back in the main activities have also affected the development of associated experimental techniques. None of the previously listed items have been reported as progressing for the present review.

G. Schweiger and M. Fiebig (DFVLR (PWG)) have further developed the now well established electron beam fluorescence technique for the measurement of temperatures up to 2500 K. They are now placing more emphasis on Raman scattering for concentration, density and temperature measurements with high spatial resolution. Both an argon ion laser and a pulsed 100MW ruby laser are being developed for use in mixing experiments and in flames. Refs 31 and 32 give details of DFVLR (PWG) work on Raman scattering in high density gases. Meanwhile, K. Stursberg reports that the laboratory continues to investigate one of the main problems with the electron beam technique, namely the effect of secondary electrons produced by the primary electron beam. It is understood that J. Harvey (ICL) plans to evaluate the use of the electron beam technique in high density, hypersonic, boundary layers. Further work on these techniques, but at lower densities, is reported in section 346.

DFVLR (PWG) are developing a special thermocouple probe for high enthalpy flow measurements[33]. A multiparameter study has been conducted, both experimentally and by computation, to optimise the probe design. At RAE (F), K. Dolman and G.T. Coleman, are also actively developing a high output heat transfer gauge for wind tunnel and flight measurements. It has already been tested in wind tunnels at RAE (F) and DFVLR (PWG) and on a Skylark sounding rocket.

There are two further developments in the measurement of surface temperature and hence heat transfer rate which have made significant progress since the last report. K.A. Bütefisch has used liquid crystals to display surface temperature distributions on bodies in a wind tunnel; these could be used for the determination of heat transfer once a detailed calibration had been completed. One example of the application of this technique is the measurement of heat transfer rate, and boundary layer transition region, on a cone at a Mach number of 5.

An alternative technique is being evaluated by D.L. Schultz at OXU. This invovles the use of a fast acting, two channel, infrared sensor (liquid nitrogen cooled indium antimonide). Experiments in the OXU gun tunnel, at Mach 7 with

only 25ms flow duration, show that the temperature of a rough surface could be measured with a resolution of 0.2 deg K.

FFA have carried out an extensive comparison of Meier's combined pressure and temperature probe, with their own mass flow probe, in a hypersonic boundary layer. With the FFA probe, the mass flow is obtained from measurement of pressure derivatives in a closed volume with controlled temperature. Its particular advantage is that fewer parameters than normal are involved in the data reduction and the risk of shock detachment at the probe tip is reduced. Further details can be found in the current Eurovisc report (item 17.3) and Refs 35 to 37.

Finally, R. Brun (LDSR) has carried out numerical studies of the complete flow field in a shock tube which simultaneously takes account of boundary layer effects and of finite diaphragm opening times. Although not an experimental study, this job obviously relates to experimental techniques.

319 Miscellaneous

32 LOW TEMPERATURE PHENOMENA

321 Condensation of air or component gas

Although gas condensation studies have importance in their own right, they also have more general impact on some of the topics covered in other sections, for example, in the production of molecular beams, the use of free jets for aerodynamic testing, and in the determination of conditions in the hypersonic wind tunnel. Since the last report, O.F. Hagena of IKK, has produced[38] a very interesting and informative review on cluster beams, which includes a discussion of condensation in nozzles. Further information of the work of K. Bier (TUTI) is contained in Ref 39; Bier's present work is mainly concerned with spontaneous condensation of CHF_2Cl in an annular dual nozzle. Reports have also been received of the progress at CENS (R. Compargue) who is concentrating research[40-42] on the properties of free jets, especially the penetration of background molecules, and techniques for skimming the free jet to produce high quality molecular beams. This work is to a large part directed towards isotope separation.

33 HIGH DENSITY PHENOMENA

This section is also mainly concerned with background information essential to progress in the main sections covered by this report. B.E. Richards has continued his studies at VKI on the thermodynamic properties of dense nitrogen[43-45]. Detailed measurements have been made of the pressure, temperature

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and volume of a fixed mass of air or nitrogen by a transient technique. Correlation of the data indicates, tentatively, that this technique is quite accurate, but that the sodium line reversal method appears to be rather inaccurate, due to its sensitivity to small quantities of impurities in the samples tested.

VKI appear to be the only major source of information and research, within Europe, on high density phenomena, mainly due to the high performance that can be achieved in the VKI piston driven shock tunnel. The results of a VKI performance assessment of an advanced piston driven tunnel for full simulation of Mach number, Reynolds number and enthalpy is contained in Ref 46. The VKI facility have more recently been converted to a double-diaphragm mode of operation* which produces shock Mach numbers of 18 in helium. Computations are also being made[47] for a Schultz and Jones type isentropic light piston tunnel for simulating real gas effects over blunt bodies associated with planetary atmosphere entry. The plan is to use heated C_2F_6, which has a low γ value, to give a high density ratio across the bow shock.

331 Properties of dense air or component gases

332 High density effects in hypersonic flows

34 LOW DENSITY PHENOMENA

Reference to the previous report will show 26 entries in this section, whereas the present report has 33 contributions. This has largely been brought about by an increase in the number of people, and laboratories, approached for this review. It also suggests, however, that there has been rather less of a cut-back in this field than in research on high density and/or high temperature phenomena. Nevertheless, we have not received contributions from CNRS, ONERA, ULC, UPaMT or VKI as previously. The main areas of new work, or work which was not included in our last report, concerns DFVLR (PWG), IMPU, OXU, PTMR and USM.

In the context of rarefied gas dynamics there has been a notable major contribution by C. Cercignani with the publication of Ref 48, dealing with the theory and application of the Boltzmann equation. This work has an impact in several of the following sub-sections.

341 Air-particle/surface interactions

R.G. Lord at OXU has continued studies[49] of the tangential momentum transfer between rare gases and metal surfaces. His experiments are conducted under ultra-clean vacuum conditions such that the influence of surface conditions can

* Similar to the facility at ANU Australia (Sandeman).

be evaluated. Lord also reports progress on the setting up of a cryogenically pumped aerodynamic molecular beam facility[50], which will be used for molecular beam scattering experiments, including velocity analysis facilities[50]. Part of Cercignanis' present research programme is also being devoted to establishing theoretical models for gas surface interactions.

342 Basic molecular theory of continuum flows

In the kinetic theory of gases the method of discrete velocities, in which particle velocities are represented by a given finite set of vectors, has been used by several people. So far all the investigations have involved the use of models with a very small number of velocity vectors and for several rarefied gas dynamic problems these models give a very simple physical picture of the phenomena and rather good quantitative results. R. Gatignol is working on a generalised model[52-54] based on this approach and plans to build up the relevant theory for application to particular gas flow problems such as shock wave structure and steady and unsteady Couette flow. One particular aspect which is receiving attention is the representation of particles which have undergone an interaction with a solid boundary.

N. Bellomo (PTMR) is studying the application of kinetic theory to the vaporisation and condensation of liquid droplets in a rarefied stream; details of this work can be found in Refs 55 and 56.

343 Structure of strong plane or curved shock waves

The structure of shock waves in gases, using a range of molecular interaction laws has been obtained by D.S. Butler at USM using an orthogonal expansion method for a solution to the Boltzmann equation. A new 'fast' method has been devised for the computation of the collision term which allows computation of three-dimensional distributions with only a small increase in effort above that for two-dimensional cases; this opens up the possibility of computing solutions for the full Boltzmann equations in situations where the distribution is three-dimensional in velocity space.

Refs 57 and 58 describe H. Alsmeyer and B. Schmidt's (TUKS) measurements of the density distribution through shock waves in argon and nitrogen in the Mach number range 1.5 to 10, using an electron beam absorption technique. Using a modified absorption law for the beam the new experimental data shows excellent agreement with Bird's Monte Carlo simulation theory in the Mach number range for a repulsive intermolecular force law. Agreement is also good with the Mott-Smith

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profile when the same interaction law is used, especially at low Mach numbers. The authors suggest that their data shows clearly the failure of the Navier-Stokes and BGK-solutions, even for the lowest Mach number. Although the experimental results in nitrogen agree reasonably well with other shock tube measurements, they show substantial deviation from Arssen and Talbot's wind tunnel data. Rotational relaxation in nitrogen was found to be very fast for all Mach numbers. Consequently the coupling between rotational and translational relaxation can be expected to be very strong.

G. Adornit (RWTH) has also measured density distributions through shock waves[59,60], but in their case in inert gas and in water vapour and only at low Mach numbers. They, too, find a discrepancy between their experimental results and the Navier-Stokes solution but a good agreement with a Monte Carlo solution. The electron beam absorption and fluorescence techniques are being used by H. Grönig (THARL) for the measurement of density distributions through reflected shock waves; further details are given in Ref 61.

In connection with an experimental investigation of the non-ideal behaviour of the flow behind the primary shock[62,63] in a tube at low initial pressure, B. Schmidt (TUKS) has found good agreement with a laminar boundary layer theory. It appears that the shock front curvature data agreed well with a theory due to de Boer, even within one mean-free-path from the wall. This finding has led to an experimental study of the shock structure close to the wall using a differential laser interferometer. This problem is also being tackled by a Monte Carlo simulation technique.

344 Structure of slipping boundary layers

G. Koppenwallner and H. Legge are involved in experiments aimed at measuring the drag of flat plates throughout the whole transitional range. Early results were obtained in the free molecule and near free molecule regimes using a special selection of the DFVLR (G) hypersonic vacuum wind tunnel. More recent experiments are aimed at the near continuum regime. One important finding[64] is an overshoot on the flat plate drag as the free molecule limit is approached, ie where the drag is due purely of viscous shear stress.

A series of experiments have been conducted by J. Harvey's group at ICL on flat plates[65] with and without forward facing steps in a low Reynolds number, hypersonic, wind tunnel. This has provided very accurate data which has been compared with direct simulation Monte Carlo predictions[66,67]. Surface pressure and flow field density, as well as rotational temperature, measurements have been

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obtained, the latter two using the electron beam fluorescence technique. A special feature of this method, as used at ICL, is employment of a digital data recovery system for resolving the emitted light spectrum. The study has now been extended to experiments on an 'axisymmetric' flat plate, ie a sharp leading edge hollow cylinder, as this avoids problems introduced by cross flow effects on finite width plates. This study again confirms the value of the direct simulation technique, which has been developed at ICL to the state where diatomic collision models can be incorporated into the computation.

The flow of a gas mixture in a finite length slit with moving walls is being investigated numerically by K.G. Roesner (DFVLR (F)). Although this is primarily aimed at separation phenomena of the gas species, a wide range of Knudsen numbers are being covered, attention is also being given to the wall Knudsen layer for mixed gas flows. H. Lang and W.J.C. Müller have applied[68,69] a general gas-liquid surface interaction law for mass and energy transfer of monatomic gases to a wall. The macroscopic slip velocity, temperature jump, thermal creep velocity and diffusion slip velocity have been calculated for a mixture of gases, including the case of an anisotropic surface. So far the computations have been concentrated on binary mixtures. Surface anisotropy produced several new slip effects.

345 *Rarefied hypersonic flows*

The last Eurohyp report noted the growth in studies concerned with rarefied flow over complex shapes; this was related to the strong interest then aroused by Space Shuttle and by the possibility of European participation in the design and manufacture of that vehicle. As we now know, these hopes did not come to fruition and some of the European research on topics related to high altitude flight have been curtailed. Nevertheless, good progress has been made in our understanding of certain aspects of low Reynolds number external flows, mostly through the activities of a few remaining institutes such as DFVLR (G), DFVLR (PWG) and OXU and ICL.

There are three items in the present review concerned with the leading edge problem in hypersonic rarefied flow. Fiebig and Becker at DFVLR (PWG) report[70] the measurement of temperature and pressure in the flow field about a sharp leading edge flat plate using both the electron beam fluorescence technique and pitot probes. The free-stream flow in these experiments, which was carefully monitored, was partially ionised nitrogen and argon. Comparisons have

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been made with available theory and the experimental programme is being extended to a study of flow incidence effects. Experiments are also planned on shock impingement onto the plate; this will clearly provide a very interesting comparison with the step induced separation data obtained by Harvey under item 344.2. Harvey and Davis are using a specially developed form of their direct simulation Monte Carlo technique to study the sharp leading edge flow[71-73]. In particular a hybrid approach to collision modelling is employed using a classical collision for energetic encounters and a statistical model for the near equilibrium situation near the leading edge. F.J. Hendelang[74] (HBN) is also working on the problem of supersonic flow near the leading edge of a sharp flat plate, but in this case in the free molecule flow limit. He is using a modified Bessel function to solve the integrals in a new theoretical approach.

An extension of the classical flat plate study is being undertaken by DFVLR (PWG) with an experimental study[75] of swept leading edge plates in rarefied hypersonic flow. M. Becker and F. Bachour are measuring surface pressure and heat transfer, as well as pitot pressures in the flow field. Their objective is a comparison with the continuum flow situation.

There is still a reasonable amount of work under way on the flow over slender bodies with attached shock waves, such as cones. H. Legge DFVLR (G) has reported a particularly interesting experimental study of the drag of cones at zero incidence in the near free molecule flow regime, with a special emphasis on the influence of body wall temperature[76]. Information about gas surface interaction phenomena is being obtained by making comparative measurements in flows of helium, argon and air. More recently the measurements have been extended to smaller Knudsen numbers, ie towards the continuum flow limit, and plans for future tests include the influence of surface finish on aerodynamic forces. The local heat transfer rate and recovery factor have also been measured for these bodies under similar flow conditions. This work will make a very valuable basis for comparison with a current programme[77] at OXU (C.L. Brundin), where the magnetic suspension balance has been significantly improved so that it can be used to measure the drag of slender cones. In the latter case the data will be completely free of sting interference effects. G. Schweiger and his co-workers at DFVLR (PWG) have reported their work on the flow fields and heat transfer rates around cones and hemispheres in rarefied flow. This work has now been completed and full details are given in Refs 78 to 80.

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The computation of free molecule flow over convex walls is now well established and relatively straightforward, but the more general case for real body shapes still causes problems. This is because of the difficulty posed by concave walls, where the source of impinging molecules may be from infinity or from another part of the body. W. Wuest DFVLR (G) is persuing two different approaches to this type of problem. One is based on an iterative process which converges rapidly for plane, axisymmetric or three-dimensional bodies; an example for which computations have already been made is the caret wing. A particular aspect of this work is the influence of different surface interaction models; it thus provides a sound theoretical base for the experimental work reported in item 345.5. R. Friedrich of TUMS is studying the non steady flow field in the vicinity of an impulsively started flat plate for a collisionless monatomic gas, using a solution of the Boltzmann equation[83-89]. This work is now extended to heated or cooled cylinders and the trailing edge of a flat plate at incidence. The latter is aimed at questioning whether or not the development of vortices can be predicted using only binary encounters.

Turning to the problem of blunt body flows with detached shock waves, an excellent and very comprehensive study of the drag of spheres in hypersonic rarefied flow has been completed by Hadjermichalis and Brundin (OXU). This included the influence of wall temperature[77]; strong effects were avoided by the use of magnetic suspension balance.

G.T. Coleman and S.C. Metcalf (RAE (F)) have been conducting experiments[90] on the variation of heat transfer rate to hemisphere cylinders and blunt ended cylinders throughout the transition from near free molecular to near continuum flow. The study shows that the departure from a stagnation point heat transfer rate dependent on an inverse root nose radius can be predicted using Cheng's viscous interaction parameter. This latter term correlates data for both body shapes throughout the transition regime. Further wind tunnel data, and limited flight trials using a Skylark research rocket, aim at extending this data base[91] over a wide range of Mach numbers, Reynolds numbers and gas species. A related, but independent, study is being made by J.K. Harvey and E. Galloway at ICL, at high Mach numbers. At present the work is concentrated on heat transfer rate to bluff cylinders, but this will be complemented by surface pressure and flow field density and temperature. The direct simulation Monte Carlo computational technique is also being applied by ICL to these geometry and flow conditions. The method has shown a great deal of promise when applied to the RAE data[92].

One of the particular advantages of the magnetic suspension system as used at OXU (item 345.6) is highlighted in its use for interference-free wake studies. Much excellent data has already been obtained on the wake of spheres at low Reynolds numbers[93,94] and OXU plan to extend the technique to provide cone wake data.

346 Experimental techniques

Much of the progress on the work described in the preceding sections of this report depended for success on the application of advanced apparatus and high experimental skill. European laboratories have made a very significant contribution to the overall data base now available, both as regards quality and quantity; this is particularly true if regard is taken of the limited number of people deployed in these pursuits. Details of the experimental techniques have already been given in many cases but special mention should perhaps be given to certain items, such as the progress that has been achieved in the measurement of heat transfer by DFVLR (G), OXU and RAE (F). Also DFVLR (PWG) have made extremely good progress in both the exploitation and understanding of arc heated flows for wind tunnel testing. Mention should also be made of OXU work in the development of the magnetic suspension/force balance which has resulted in new definitive data on sphere drag.

Perhaps one of the most significant advances in experimental techniques in Europe has come from the utilisation of electron beam induced fluorescence. This method of measuring gas density, rotational temperature and velocity in the free-stream is now very well established, and good progress is being made in applying the technique in the vicinity of body surfaces. An excellent review of the application of this technique is contained in Ref 95, prepared by K.A. Bütefisch of DFVLR (G). More recently this laboratory has concentrated on improving the accuracy of data near to the wall of bodies so as to determine the influence of wall temperature on the developing flow field around the body. Measurements have been made over cones with different cone angles. DFVLR (G) have also been making velocity measurements in free jets, where the accuracy was high enough to critically assess different theories accounting for the freezing of rotational temperature. Although the electron beam technique has proved to be rather more difficult to interpret than originally envisaged, more complex analytical procedures are being developed to deal with such problems as secondary electron contributions. Such developments come from very careful experimental and theoretical studies, such as conducted at OXU. P. Rockett and

C.L. Brundin have almost completed a detailed study of translational and rotational temperature measurements in flowing nitrogen. Improvements in the electron beam technique by ICL, aimed at simplifying the application in wind tunnel experiments, have already been mentioned. Significant contributions to the technique have also been made by DFVLR (PWG), who have also investigated a Raman scattering technique using a high powered laser.

R.G. Lord (OXU) is developing an alternative technique in which the primary scattering of a narrow, high energy, electron beam by a partially ionised gas stream is measured. So far, it has been shown that the density of neutral particles can be obtained by this method[97] and the measurement of charged particle densities is now being evaluated.

The application of molecular probes for the measurement of speed ratio and particle concentration in low density flows is usually hindered by the fact that free molecular flow around the probe cannot be maintained because of limited pumping capacity. K. Bier (TUTI) is attempting to overcome this problem by studying[98] the deviation between real and ideal values of both speed ratio and density over a range of conditions in various gases in subsonic and supersonic flow. The DFVLR (PWG) group (M. Becker, J. Bäte and D.G. Papanikas) have been developing techniques for the measurement of density and total temperature in the upper atmosphere using sounding rockets. This is a joint European project for providing knowledge[99] on the 'winter anomaly' effect and the first flight was made in January 1976.

Several of the experimental techniques used in the measurement of properties of rarefied flows, such as in item 346.4, involve an assumption or requirement for local free molecular flow. Thus, computational techniques for free molecule flow have importance to experimental studies. D.C. Pack and R.J. Cole have devised relatively simple methods of computation for such flows based on complementary bivariational principles[100,101]. One of their early studies involved a general solution of the Clausing problem of the conduction of circular tubes. This has been applied to the prediction of the pressure measured by an inclined tube set in the surface of a plate or body in local free molecular flow. Particular computations have been made for a pair of tubes inclined at 45° to the surface, one forward and one backward, as a function of tube length to diameter ratio. It was shown[102] that the ratio of pressures measured by the two tubes can be directly related to the speed ratio of the external flow. A wind tunnel evaluation of the technique is being made at RAE (F) (S.C. Metcalf and G.T. Coleman).

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Although little mention has been made in this report of the aerodynamic separation of isotopes this is an interesting and very important practical application of internal hypersonic rarefied gas flows. The subject is now attracting considerable attention in the USA as well as Europe* and it is felt that groups experienced in hypersonic flows could, and should, make a significant contribution. Consideration is being given to including this topic in future Eurohyp reports. Meanwhile, reference might be made to the excellent work of R. Campargue on the jet membrane technique and the use of separation probes. The former technique is based on the partial invasion by background molecules into an underexpanded free jet. If a gas or isotropic mixture is introduced into the nozzle chamber and outside the barrel shock, the background penetration is differential and a mixture enriched in the lighter species is attainable by skimming the free jet. This basic technique has been much developed by Campargue. The separation probe technique utilises the bow shock wave induced by a probe operating in a supersonic stream. The gas removed from the stagnation region, collected by the sampling orifices, is enriched in the heavier species. These techniques are described in more detail in Refs 103 and 104.

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77	Hadjurmichalis C.L. Brundin	Effect of wall temperature on sphere drag. 9th Rarefied Gas Dynamics Symposium, Göttingen Also in OUEL Report 1062/73
78	G. Schweiger *et al*	Temperature measurements. ICIASF 1975 Record, CHO 993-6 AES, pp 229-236 (1975)
79	M. Becker *et al*	Strömungsfeld + Oberfläche stumpfer Körper. Abhandl. des Aerodyn. Inst. der TH Aachen, 22, pp 140-146
80	F. Bachour	Einfluss der Körperform auf den Wärmeübergang. DLR Mitt., 75-20, pp 83-96 (1975)
81	W. Wuest	Das Dichtefeld um einen unsymmetrisch angeblassenen Keil in freier Molekülströmung. DFVLR-AVA IB 252-74/H02 (1974)
82	W. Wuest	Die Berechnung von Strömungsfeldern um dreidimensionale Körper in grosser Höhe. DLR FB 75-45 (English translation by ESA) Short version preprint 75-050, 26, ICAS Congress, Lisbon (1975)
83	R. Friedrich	Gaskinetische Behandlung instationärer Strömungsvorgänge bei mässig bis stark verdünnten Gasen. Dissertation, TU München (1972)
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86	R. Friedrich	The impulsively started and heated finite flat plate in a collisionless gas. Mechanics Research Communications, Vol 1, pp 89-93 (1974)
87	R. Friedrich	Two-dimensional compression and expansion of a collisionless gas. Proceedings of the 9th International Symposium on Rarefied Gas Dynamics, Göttingen (1974)
88	R. Friedrich	Anlaufströmungen um längs- und querbewegte Platten bei sehr grossen Knudsenzahlen. Habilitationsschrift, TU München (1974)
89	R. Friedrich	Zweidimensionales Kolbenproblem im Grenzfall freier Molekülströmung. ZAMM 55, pp 122-125 (1975)
90	S.C. Metcalf G.T. Coleman C.J. Berry	Heat transfer to bluff faced and hemispherical faced cylinders between continuum and free molecular flow limits. Proceedings of the 9th Rarefied Gas Dynamics Symposium, Göttingen, July 1974 DFVLR Press, Porz Wahn, West Germany
91	G.T. Coleman S.C. Metcalf C.J. Berry	Some further results on stagnation point heat transfer in the transition flow regime. RAE Technical Memorandum Aero 1679 (1976)
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94	Muthoo C.L. Brundin	Study of sphere near wakes. 9th International Rarefied Gas Dynamics Symposium, published by DFVLR Press (1974)
95	K.A. Bütefisch D. Vennemann	The electron-beam technique in hypersonic rarefied gas dynamics. Progress in Aerospace Science, 15 (217) (1974)
96	P. Rockett C.L. Brundin	A study of thermal states of nitrogen by the method of electron beam induced fluorescence. 9th International Rarefied Gas Dynamics Symposium, Göttingen, DFVLR Press, Porz-Wahn, Germany (1974)
97	R.G. Lord	Rarefied Gas Dynamics; Ed. Dino Dini, ETS (Pisa), Vol I, p 655 (1971)
97a	R.G. Lord	J. Phys. D. Appl. Phys., 3, 1480 (1970)
98	M. Firnhaber	Zur Untersuchung von Strömungen verdünnter Gase mit Miniatur-Drucksonden bei nicht-molekularer Anströmung der Sonde. Dissertation, Universität Karlsruhe (TH)
99	D.G. Papanikas J. Bäte	Pitot pressure measurements for atmospheric density determination. Winter anomaly/Trace constituents, Campaign Handbook, Part 2 - Science, pp 57-60
100	R.J. Cole D.C. Pack	Drag and conductance of free molecular flow through a rectangular duct. Proc. 9th International Rarefied Gas Dynamics Symposium, Göttingen, pp D19.1-D.19-9, DFVLR Press (1974)
101	R.J. Cole D.C. Pack	Some complementary bivariational principles for linear integral equations of Fredholm type. Proc. Roy. Soc. A (in the press)

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103	R. Campargue *et al*	8th Rarefied Gas Dynamics, Stanford, USA (1972)
104	R. Campargue *et al*	Review paper "On aerodynamic separation methods". 1st European Nuclear Conference, Paris; In Progress in Nuclear Energy Series, Pergamon Press, Oxford, New York and Paris (1975)

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LIST OF PROGRAMME ITEMS

FIELD 1 LIFTING BODIES - Editor: L.C. Squire

11 BODIES DESIGNED FROM KNOWN FLOW FIELDS

111 Design methods

111.1 No work reported.

112 Theory of off-design

112.1	Survey of theories applicable to caret wings under off-design conditions	ILR U. Ganzer H. Hoder
112.2	Methods for calculating non-linear flow with attached shock waves over conical wings and wing-bodies	USoAA R.A. East

113 Experimental work

113.1	Experimental results for a caret waverider under off-design conditions	ILR U. Ganzer H. Hoder
113.2	Force measurements of lifting re-entry shapes with concave lower surfaces at high angles of attack	VKI B.E. Richards
113.3	Pressure distributions and shock shapes on waveriders	ICL J.K. Harvey Mrs E. Galloway
113.4	Experimental investigations on the lee-side of caret wings at incidence	TUBS G. Strömsdörfer

12 FLOW ABOUT BODIES OF GIVEN SHAPE

121 Axisymmetric bodies

121.1	Calculation of stationary inviscid supersonic flow about blunt axisymmetric bodies at incidence	NLR C.R. Trass
121.2	Flows over axisymmetric blunt bodies with concave conical foresections	VKI B.E. Richards
121.3	Free flight measurements of aerodynamic force coefficients	OXU D.L. Schultz
121.4	(a) Pressure distribution measurements on an axisymmetric body without and with delta wings or Mach numbers 4 and 7 (b) Force-balance tests of configuration in (a) (c) Comparison of interference loads with theory	FFA E. Larson

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121.5	Heat transfer on re-entry bodies	RAE (F) K.A. Dolman
121.6	Hypersonic rarefied flow over cones at incidence	DFVLR (G) K. Kienappel G. Koppenwallner
121.7	Density and temperature measurements by electron beam at the stagnation points of blunt bodies	DFVLR (PWG) G. Schweiger M. Fiebig
122	<u>General shapes</u>	
122.1	A finite difference method for three-dimensional supersonic flow fields	USaCC R. Walkden
122.2	Flow around low aspect ratio wings at supersonic and hypersonic speeds	CIT J.L. Stollery
122.3	Flow variation over a flat plate with sudden change in incidence	CNRS M.F. Scibilia J. Allgegre C. Matrand
122.4	Investigation of characteristics of lifting wings - conical wings	UCED L.C. Squire
122.5	Uniformly valid thin-shock-layer theory for three-dimensional hypersonic flow	DFVLR (A) H. Schwarze
122.6	Newtonian aerodynamic forces from Poisson's equation	RAE (B)
122.7	Drag reduction of a sharp flat plate in a hypersonic rarefied flow by means of a fore leading edge	CNRS M. Bisch
122.8	Investigation of the characteristics of lifting wings - non-conical wings	UCED L.C. Squire
122.9	Investigation of upper surface flows	UCED L.C. Squire
122.10	Leeside flows on delta wings at supersonic speeds	ILR J. Szodruch
122.11	Forces on tactical missile shapes	VKI B.E. Richards W. Stahl
122.12	Six component free flight measurements in the gun tunnel	DFVLR (PWG) W. Wyborny
122.13	Heat transfer measurements on a delta wing with blunted leading edges in hypersonic flow	FFA S. Lundgren

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122.14	Flow about cones at large angles of attack	TUD W.J. Bannink
122.15	Flow in three-dimensional expansion regions	TUD T.P.M. Hendriks
13	<u>INTERFERENCE PROBLEMS</u>	
131	<u>Corner flows</u>	
131.1	Investigations of the hypersonic flow field in corners. Part I Corners with unswept leading edges. Part II Corners with swept leading edges	TUBS G. Strömsdörfer W. Mollenstädt
131.2	Investigations on corner flows at hypersonic speeds	DFVLR (PWG) H. Pfeiffer H. -J. Schepers
132	<u>Intersections and interacting bodies</u>	
132.1	Separation at hypersonic speeds	ICL J.K. Harvey R. Hillier J.R.A. Lowder
14	<u>CONTROLS AND DYNAMICS</u>	
141	<u>Aerodynamic controls</u>	
141.1	Aerodynamic control of missiles with a deflected spike in front of the body	DFVLR (PWG) W. Wyborny
141.2	Shock wave boundary layer interactions on convex walls	VKI J.J. Ginoux
141.3	Experimental study of reaction control and its aerodynamic interaction in hypersonic rarefied gas flows	DFVLR (G) G. Hefer
141.4	Investigation of unsteady shock interferences on a wing-flap configuration	FFA S. Lundgren
142	<u>Stability and control problems. Complete vehicles</u>	
142.1	Experimental and theoretical investigation of some hypersonic stability and control problems of two-dimensional wedges and delta wings of various cross section shapes	USoAA R.A. East
142.2	Dynamic stability of axisymmetric shapes	USoAA R.A. East
142.3	A novel tunnel starting technique	ARA D. Morton

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142.4	Dynamic stability measurements	ARA D. Morton
142.5	An HST project based on waverider concept	ILR U. Ganzer H. Hoder
142.6	Measurements at M = 7 of the lift, drag, pitching moment and pressure distributions of flared bodies	ARA D. Morton
142.7	Aerodynamic coefficient and stability derivatives at hypersonic velocities	HBN F.J. Hindelang

FIELD 2 PROPULSION AERODYNAMICS - Editor: G. Winterfeld

21 THEORY OF FLOW WITH HEAT ADDITION

211 Heat addition over finite regions

211.1	Theoretical study of flow fields with heat addition	RAE (F) E.C. Broadbent

22 FLOW WITH HEAT ADDITION - EXPERIMENT AND THEORY

221 Diffusion flames

221.1	Structure and stability of flames	CIT J.F. Clarke
221.2	Prediction of non-equilibrium turbulent diffusion flames including complex chemical kinetics	UoSIT J. Algermissen
221.3	Mixing and combustion of transverse injection of fuel gas into hot supersonic air streams	TUKT K. Bier
221.4	Heat addition by combustion of pyrophoric fuel	DFVLR (B) M. Kallergis
221.5	Turbulent combustion studies	UoSAA K.N.C. Bray

222 Supersonic combustion with shock waves

222.1	Shock induced ignition and combustion at a wedge in a flow at M = 4	DFVLR (B) M. Kallergis
222.2	Theoretical and experimental investigation of shock induced combustion of hydrogen in a supersonic stream	UoSIT J. Algermissen
222.3	Spherical turbulent flames	IPC H.G. Wagner

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223	External heat addition	
223.1	Experimental study of a hypersonic near wake of a hemisphere-cylinder including base injection	CNRS C. Bische
223.2	Base-pressure reduction by hydrogen combustion	DFVLR (B) M. Kallergis
223.3	External heat addition on flat plates and bodies revolution	DFVLR (PWG) F. Maurer J. Niezgoka H. Post
223.4	External heat addition	DFVLR (PWG) H. Pfeiffer E. Will
224	Dual-mode combustion - miscellaneous	
224.1	Flame holders and turbulence generators	ITS T. Valdsoo
225	Kinetics of combustion	
225.1	Study on combustion stabilized by mixing of burnt gases with fresh gases	ENSMA J.C. Bellet
23	INJECTION AND MIXING PROBLEMS	
231	Wall injection, including film cooling	
231.1	On the aerodynamics of fuel injection from a wall into a supersonic stream	ILR U. Ganzer
231.2	Combined multi-jet injection studies	TUMF H. Rick
231.3	Wall injection including film cooling	OXU D.L. Schultz
232	Coaxial injection	
232.1	Counter flows in supersonic speeds	ILR J. Szodruch H. Hoder
232.2	Experimental and theoretical investigations on the hypersonic flow past blunt bodies of revolution with coaxial ejection	TUBS G. Strömsdörfer
232.3	Super and hypersonic jets and mixing	GHDF M. Fiebig

234	Boundary layer investigation	
234.1	Numerical analysis of chemically-reacting boundary layer flows with finite-rate chemistry	UoSIT J. Algermissen
234.2	Hupersonic turbulent boundary layer on flat plate	ICL J.K. Harvey R. Hillier R.P. Bartlett A.J. Edwards
234.3	Theoretical studies of hypersonic boundary layers	ULUC K. Stewartson
234.4	Heat transfer measurement in a ramjet inlet	FFA S. Lundgren
24	LIFTING PROPULSIVE BODIES	
241.1	Ignition and external combustion in the flow past a lifting body	DFVLR M. Kallergis
25	EXHAUST PLUMES	
251	Theoretical studies	
251.1	Interaction between exhaust plumes and external surfaces in rarefied flow conditions	CNRS J. Allegre J.C. Lengrand M. Raffin
251.2	Nozzle contours for maximum thrust	IMR N. Bellomo
252	Experimental studies	
252.1	Heat transfer measurements for a rocket plume impinging on a flat plate	RAE (F) J.E.G. Townsend
FIELD 3	FLOW OF REAL GASES - Editor: S.C. Metcalf	
31	HIGH TEMPERATURE PHENOMENA	
311	Properties of hot air or component gases	
311.1	Transport phenomena in shock induced boundary layers	THARL Prof Dr H. Grönig
311.2	Calculation of transport properties in hot gases	DFVLR (PWG) A.W. Neuberger

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312 Hypersonic equilibrium flows

313 Relaxation effects in hypersonic flows

313.1	Nonlinear waves in gases with weak influence of relaxation	THD H. Buggisch
313.2	Transport properties of vibrationally relaxing flows	LDSR R. Brun
313.3	Influence of the oxygen vibrational and dissociation relaxation on the shock reflection	TUKS H. Oertel, Jr. B. Schmidt
313.4	Oxygen dissociation relaxation behind stationary weak oblique shocks, located in partly dissociated oxygen	TUKS H. Oertel, Jr. B. Schmidt
313.5	Shock-shock interaction in hypersonic flow	DFVLR (PWG) G. Schweiger M. Becker D.G. Papanikas
313.6	Dissociation rate in strong shock waves	HBN F.J. Hindelang
313.7	Heat transfer to catalytic and non catalytic surfaces on blunt bodies in non-equilibrium hypersonic air	USoAA R.A. East
313.8	Hypersonic stagnation flow of viscous gases with vibrational relaxation	DFVLR (D) B. Schmitt-v-Schubert
313.9	Fully dispersed shock waves - calculation methods for non-equilibrium flow regions	UManMF N.H. Johannasen
313.10	Thermo-gas dynamic problems of mixing in non-equilibrium flows	DFVLR (PWG) M. Becker A.W. Neuberger W. Krahn
313.11	Theoretical and experimental investigation of vibration, dissociation and ionisation of mixtures of carbon dioxide and oxygen	THAM G. Adomeit G. Berg
313.12	Numerical solution of the master equation	HBN F.J. Hindelang
313.13	Non-equilibrium nozzle flows	DFVLR (PWG) & GHDF M. Fiebig
313.14	Population inversion in blast waves	LDSR R. Brun

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313.15	Non-equilibrium boundary layers	UEFM M. Jischa
313.16	Chemically reacting boundary layers	UEFM B. Gampert
313.17	Solution of the hypersonic boundary layer equations with a self adaptive variable order difference method	TUKR W. Schönauer
314	<u>Radiation effects in hypersonic flows</u>	
315	<u>Ablation effects in hypersonic flows</u>	
315.1	High enthalpy wind-tunnel experiments on models with CFC and PTFE ablating surfaces	DFVLR (PWG) K. Kindler
316	<u>Optics and electrics of hypersonic flows</u>	
317	<u>Magnetoaerodynamic phenomena</u>	
318	<u>Experimental techniques</u>	
318.1	Temperature, density and concentration measurements by electron beam fluorescence and laser light scattering	DFVLR (PWG) G. Schweiger M. Fiebig
318.2	Opto-diagnostic measurement techniques	DFVLR (PWG) K. Stoursberg W. Krahn K. Erhardt K. Wanders
318.3	Parameters influencing heat transfer in high enthalpy flows	DFVLR (PWG) K. Kindler
318.4	Temperature and heat transfer measurements with liquid crystals	DFVLR (G) K.A. Bütefisch
318.5	Infra red sensing of transient surface temperatures to obtain heat transfer rates	OXU D.L. Schultz
318.6	Comparative temperature measurements in a hypersonic turbulent boundary layer by means of a Meier probe and FFA mass flow probe	FFA G. Houstadius
318.7	Interaction of boundary layers and inviscid flows	LDSR R. Brun
318.8	Optical techniques for determining conditions at the end wall of a shock tube	EUT M.E.H. van Dongen

32	LOW TEMPERATURE PHENOMENA	
321	Condensation of air or component gases	
321.1	Spontaneous condensation within expanding stream flows in a wide pressure range	TUTI K. Bier
322.2	Nozzle beams (10^{-2} to 40 eV) obtained by skimming pure gas or gas mixture free jets produced with extremely low translational temperature	CENS R. Campargue
33	HIGH DENSITY PHENOMENA	
331	Properties of dense air or component gases	
331.1	Thermodynamic properties of dense air and nitrogen	VKI B.E. Richards G.P. Rouel
331.2	Studies of advanced piston driven wind tunnels for simulating re-entry flight and incorporating dense gas effects	VKI B.E. Richards G.P. Rouel
34	LOW DENSITY PHENOMENA	
341	Air-particle/surface interactions	
341.1	Tangential momentum transfer in gas-surface interactions	OXU R.G. Lord
341.2	Molecular beam studies of gas-surface interactions	OXU R.G. Lord
341.3	General solution of steady linearised Boltzmann equation	IMPU C. Cercignani
341.4	Slip effects in monatomic gases	MPIS H. Lang W.J.C. Müller
342	Basic molecular theory of continuum flows	
342.1	Kinetic theory for a discrete velocity gas	UPMC R. Gattignol
342.2	Kinetic theory of liquid droplet vaporisation	PTMR N. Bellomo
343	Structure of strong plane or curved shock waves	
343.1	Application of Boltzmann equation to shock wave structure	USM D.S. Butler
343.2	Shock structure in argon and molecular nitrogen	TUKS B. Schmidt

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345.8	The impulsively started and heated cylinder in a collisionless gas	TUMS R. Friedrich
345.9	Heat transfer to simple shapes in the transition flow régime	RAE (F) G.T. Coleman S.C. Metcalf
345.10	Flat-ended cylinders in rarefied flow	ICL J.K. Harvey Mrs E. Galloway
345.11	Near wake structure in hypersonic low Reynolds number flows	OXU C.L. Brundin
346	<u>Experimental techniques</u>	
346.1	Application of the electron beam technique for measurement of density, velocity, rotational and vibrational temperatures	DFVLR (G) K.A. Bütefisch
346.2	Measurement of gas properties using luminosity excited by an electron beam	OXU C.L. Brundin
346.3	Electron scattering in partially ionised gases	OXU R.G. Lord
346.4	Investigation of rarefied gas flows with molecular pressure probes	TUTI K. Bier
346.5	Density determination by pitot pressure and total temperature measurements with sounding rockets	DFVLR (PWG) M. Becker J. Bäte D.G. Papanikas
346.6	Free molecular flows through tubes	USM D.C. Pack R.J. Cole
346.7	Techniques for aerodynamic separation of gases and isotopes	CENS R. Campargue

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Appendix A

RECENT EUROMECH MEETINGS ON RELATED TOPICS

EUROMECH 57

THE DYNAMICS OF RAREFIED GASES

University of Strathclyde, Glasgow, Scotland
19 to 21 March 1975

This Colloquium was the fifth of a series of Euromech meetings devoted to the study of motion of rarefied gases. There were 60 participants; the main centres of theoretical and experimental research were well represented, and scientists were encouraged to come from countries where there is less opportunity for regular discussions due to limited activity in the field. The representation of members by country was as follows: Belgium 2, Bulgaria 1, France 5, Germany 14, Greece 3, Italy 4, The Netherlands 1, Norway 1, Poland 4, and the United Kingdom 25.

The objectives of the Colloquium were to encourage the presentation of papers on the theoretical and numerical solution of the Boltzmann equation, on the application of theory and numerical techniques to problems of scientific and engineering importance, and on experimental work concerned with such problems, for comparison with theoretical work or as an indication of areas in which problems remain to be solved. There were 30 papers in all, giving a good mixture on these themes, and three of these were (by invitation) extended presentations, namely those of Professor C. Cercignani (Politecnico di Milano, Italy) on 'General principles and specific models for gas-surface interaction'; Professor H. Neunzert (University of Kaiserslautern, Germany) on 'Convergence of simulation methods for integro-differential equations in the theory of gas dynamics'; and Professor D.S. Butler (University of Strathclyde, United Kingdom) on 'The numerical solution of the Boltzmann equation by orthogonal expansion'. After all the lectures had been given the Colloquium closed with an informal discussion on ways in which theoretical and experimental investigations could give support to each other in the next year or so in some of the most important areas of study.

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PAPERS PRESENTED AT EUROMECH 57

Title	Author, etc
MAIN LECTURE: General principles and specific models for gas-surface interaction.	C. Cercignani Politecnico di Milano, Italy
On the boundary conditions for the Boltzmann equation at the interface of liquid-gas systems with change of phase.	N. Bellomo Politecnico di Torino, Italy
Measurements of momentum accommodation coefficients of gases on clean surface.	R.G. Lord Oxford University, UK
The measurements of molecular flux scattered from a solid surface.	G.N. Peggs National Physical Laboratory, Teddington, UK
A kinetic theory description for evaporation/condensation phenomena.	T. Ytrehus Technical University of Norway, Trondheim
Experimental and theoretical study of hypersonic viscous flow with vibrational relaxation in a circular cylinder.	K.A. Bütefische DFVLR-AVA Göttingen, W. Germany
Pressure in transition flow.	K. Kienappel DFVLR-AVA Göttingen, W. Germany
Models of the Boltzmann equation and information theory.	S.M. Deshpande University of Newcastle-upon-Tyne, UK
Disparate-mass gas theories from a thirteen-moment viewpoint.	E.A. Johnson University of Surrey, UK
On Boltzmann-like treatments for traffic flow.	S.L. Paveri-Fontana Università di Bari, Italy
Kinetic model for the interaction of non-LTE radiation with a rarefied diatomic gas.	J.R. Saraf New University of Ulster, Coleraine, N. Ireland
Rarefied gas flow in ducts of finite length with moving walls.	P. Gajewski; R. Herczynski; K. Roesner Warsaw Technological University and Albert-Lugwigs-Universität, Freiburg, W. Germany
The effect of surface roughness on velocity profiles in the Knudsen layer.	M.A. Reynolds; J.J. Smolderen; J.F. Wendt Von Karman Institute, Rhode-Saint-Genese, Belgium

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Title	Author, etc
Photophoresis of small particles.	K. Yamamoto Eindhoven University of Technology, The Netherlands
Drag of a flat plate parallel to the free stream in the range between hypersonic continuum- and free molecular-flow.	G. Koppenwallner; H. Legge DFVLR-AVA Göttingen, W. Germany
Drag of cones at different wall temperatures in near free molecule flow.	H. Legge DFVLR-AVA Göttingen, W. Germany
Influence of nose cone geometry on drag coefficients in low density transition flow.	E. Weber; M. Becker; D. Erdtel DFVLR, Institut für Angewandte Gasdynamik, Porz-Wahn, W. Germany
An integral approach to the theory of slowing down and diffusion of test particles in presence of an external force.	V. Boffi University of Bologna, Italy
Energy fluctuations of conduction electrons at low temperature.	G.J. Papadopoulos University of Leeds, UK
Space distribution of an electron swarm in a dc field.	S.L. Paveri-Fontana Università di Bari, Italy
MAIN LECTURE: Convergence of simulation methods for integro-differential equations in the theory of gas dynamics.	H. Neunzert Fachbereich Mathematik der Universität Trier-kaiserslautern, W. Germany
MAIN LECTURE: The linear Boltzmann equation and its ubiquity.	M.M.R. Williams University of London, UK
Wave structure of a chemically reacting gas flow from the kinetic theory viewpoint.	Y. Yoshizawa DFVLR-AVA Göttingen, W. Germany
Experimental and theoretical investigations of rocket plumes interacting or not with external surfaces.	J. Allègre; J.C. Lengrand; M. Raffin Laboratoire d'Aérothermique, Meudon, France
Numerical solution of low density nozzle flows.	N.K. Mitra; M. Fiebig Gesamthochschule, Duisburg, W. Germany
On the separation of skimmed molecular beams from free jet expansions of binary gas mixtures.	P. Raghuraman; U. Bossel DFVLR-AVA Göttingen, W. Germany
MAIN LECTURE: The numerical solution of the Boltzmann equation by orthogonal expansion.	D.S. Butler University of Strathclyde, Glasgow, UK

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Title	Author, etc
Density profiles in argon and nitrogen shock waves measured by the absorption of an electron beam.	H. Alsmeyer Institut für Strömungslehre und Strömungsmaschinen, Karlsruhe, W. Germany
Propagation and reflection of shock waves in a gas with discrete repartition of velocities.	H. Cabannes University of Paris VI, France
The shock wave curvature close to the shock tube wall.	B. Schmidt Institut für Strömungslehre und Strömungsmaschinen, Karlsruhe, W. Germany
Simple estimates of the conductance and drag of rarefied gas flow through bodies.	R.J. Cole University of Strathclyde, Glasgow, UK
Free molecular flow above a slightly wavy wall.	W. Fiszdon; M. Grudnicki Warsaw University, Poland
Calculation of free molecular flow fields around three-dimensional bodies with multiple reflection of molecules.	W. Wuest DFVLR-AVA, Göttingen, W. Germany
MAIN LECTURE: Slip boundary conditions.	T. Klinc Univerze v Ljubljani, Yugoslavia

EUROMECH 74

LIFTING WINGS AND BODIES AT SUPERSONIC AND HYPERSONIC SPEEDS

Churchill College, Cambridge
12 to 14 April 1976

Chairmen: Prof J.L. Stollery, Cranfield Institute of Technology
Dr L.C. Squire, Cambridge University Engineering Department

Euromech 74 was held at Churchill College, Cambridge, from Monday 12 April to Wednesday 14 April 1976 and was attended by 40 participants from five countries: Belgium 1, France 2, Germany 7, Netherlands 5, United Kingdom 25. There were a number of last minute cancellations which reduced the number of visitors from the Continent.

In all 28 papers were presented in two and a half days and the meeting ended with a general discussion.

The papers presented showed that there is still considerable interest in supersonic and hypersonic flow. It was also apparent that much of the work reported was started as a result of interest aroused at the last Euromech meeting on this topic. (Euromech 20, Aerodynamics of lifting bodies at high supersonic speeds, Churchill College, 30 and 31 July 1970.) It is interesting that 14 people who attended Euromech 20 also attended Euromech 74.

Twelve papers were mainly of a theoretical nature. One session of these dealt with various applications of thin-shock-layer theory to general shapes and showed the many advances made in this theory since the last meeting. Another session was devoted to three papers based on a revived interest in supersonic linear theory including applications of this theory to fully optimized lifting systems. There were also some papers on full numerical solutions of the equations of motion.

Fourteen papers were concerned with the experimental work and covered a wide range of topics, including low speed results on shapes designed for hypersonic speeds. It is difficult to summarise this work but it appears that there is still some work being done on fundamental aspects of lifting-body flow. However, many of the papers were obviously based on research carried out as part of programmes on specific projects. The authors were careful to stress the more fundamental and interesting aspects of this research.

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The papers presented in the final session dealt with design aspects of wings and bodies for high speed flight. These papers combined both the fluid dynamic and design problems and so set the scene for the final discussion period. This period allowed a useful exchange of views and clearly showed that most participants hoped to continue work (or at least maintain an interest) in the topic of the meeting. Specifically it was hoped that Eurohyp documents listing European work in hypersonic flow would continue, and that they should be revised at least every two years. *It was also suggested that participants should agree to circulate copies of their published papers to other people at the meeting.*

The meeting ended, as it had begun, with tributes to the late Dietrich Küchemann whose influence was reflected in most of the papers read at Euromech.

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PAPERS PRESENTED AT EUROMECH 74

Title	Author, etc
INTRODUCTORY LECTURE: The flow over delta wings.	L.C. Squire Cambridge, UK
Bifurcated shocks and solution of the flow equations for the elliptic regions.	J. Venn Bristol University, UK
Thin shock layer theory applied to wing-body combinations.	R. Hillier Imperial College, London
Attached shock flows on delta wings using thin shock layer theory.	B.A. Woods University of Canterbury, NZ
On the calculation of cone fields.	F. Walkden University of Salford, UK
The solution of elliptic problems by matching techniques - some comments on blunt body and subsonic aerofoil flows.	P. Stocker University of East Anglia, Norwich, UK
Supersonic flow past a delta wing: an experimental investigation covering the incidence range $-50 \leqslant a \leqslant 50^{\circ}$.	I.C. Richards; J.L. Stollery College of Aeronautics, Cranfield, UK
The expansion side of a delta wing at supersonic speeds.	Y.C. Sun DFVLR Göttingen, W. Germany
Lee side flow field of delta wings with detached shock waves.	J. Szodruch Technical University, Berlin
Measurements of the pitching stability of delta wings at hypersonic speeds.	R.A. East Southampton University, UK
Pressure and heat transfer distribution on delta and waverider wings in rarefied hypersonic conditions.	R.W. Jeffery; E. Galloway; J.K. Harvey Imperial College, London, UK
Measurement of forces on vehicles with concave surfaces.	B.E. Richards VKI, Belgium
An axiomatic construction of a non-contradictory linear supersonic theory.	J. Wellman Albert-Ludwigs University, Freiburg, W. Germany
An optimisation problem in linearised supersonic wing theory.	H.J. Bos University of Technology, Delft, Holland
Design of fully optimized lifting systems in supersonic flow.	A. Nastase Aerodynamics Institute, Aachen, W. Germany

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Title	Author, etc
Drag reduction of forebody shapes.	J. Pike RAE Bedford, UK
Some experimental data on the low-speed behaviour of lifting re-entry vehicles.	D.G. Edwards University of Surrey, UK, and K. Burgin University of Southampton, UK
Investigation on hypersonic aircraft at subsonic and supersonic speed.	H. Hoder The Technical University, Berlin
Conical stagnation points in the supersonic flow around slender circular cones at incidence.	P.G. Bakker; W.J. Bannink University of Technology, Delft, Holland
Experimental investigation of the supersonic flow field around a slender cone at high incidence.	C. Nebbeling; W.J. Bannink University of Technology, Delft, Holland
Turbulent boundary layer at high supersonic flow around cones at incidence, calculation and experiments.	
Blunted cone in hypersonic flow (M = 10): transition in the boundary layer as a function of radius of curvature of the nose in the case when T_w/T_0 is approximately equal to 1/3.	R. Marmey; J.P. Guibergia Institute of Fluid Mechanics, Marseilles, France
Heat transfer distributions on a 70° delta wing with flap induced separation.	A.J. Edwards Imperial College, London, UK
Force measurements on lifting shapes appropriate to re-entry conditions.	R.A. East University of Southampton, UK
Study of Reynolds number effects on pressure and normal force distribution along conically pointed circular cylinder at M = 2.3.	S.J. Boersen NLR, Holland

Papers from European institutes presented at:

TENTH INTERNATIONAL SYMPOSIUM ON RAREFIED GAS DYNAMICS

Aspen, Colorado, USA

18 to 23 July 1976

Chairmen: E.P. Muntz and J.L. Potter

Title	Author, etc
Thrust on a space-vehicle obtained by twin walls with different temperatures.	Jean J. Bernard Université Paris VI, Laboratoire d'Aérothermique, Meudon, France
A new selector for rotational state analysis in molecular beam experiments.	A. Lübbert; F. Günther; K. Schügerl Institut für Technische Chemie der TU Hannover, Germany
Quantum state dependent velocity distribution in Na_2-molecular beams.	K. Bergmann; U. Hefter; P. Hering Universität Kaiserslautern, W. Germany
Direct measurement of density and rotational temperature in a CO_2 det. beam by Raman scattering.	Isaac F. Silvera; F. Tommasini; R.J. Wigngaarden Natuurkundig Laboratorium der Universiteit van Amsterdam, Valckenierstraat 65, Amsterdam-C, The Netherlands
The slowing down of fast atoms in a uniform gas.	M.M.R. Williams Nuclear Engineering Department, Queen Mary College, University of London, UK
Flow problems for a discrete velocity gas.	R. Gatignol Laboratoire de Mécanique Théorique Université P. et M. Curie, Paris, France
A continuous slowing-down theory for test particles interacting with statistical system in the presence of an external field.	J. Dorning; C. Pescatore; G. Spiga Laboratoirio di Ingegneria Nucleare dell'Università di Bologna, Bologna, Italy
Integral Boltzmann equation for test particles in a conservative field. (1) Theory and exact solution to some stationary and time-dependent problems.	V.C. Boffi; V.G. Molinari; G. Spiga Laboratorio di Ingegneria Nucleare dell'Università di Bologna, Bologna, Italy
Integral Boltzmann equation for test particles in a conservative field. (2) Exact solutions to some space-dependent problems.	V.C. Boffi; V.G. Molinari; C. Pescatore; F. Pizzio Laboratorio di Ingegneria Nucleare dell'Università di Bologna, Bologna, Italy

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Title	Author, etc
Bound state resonance: Effect on the inelastic scattering of He and Ne from the (007) face of lift.	P. Cantini; G.P. Felcher; R. Tatarek Gruppo Nazionale di Struttura della Materia del CNR and Istituto di Scienze Fisiche dell'Università Genova, Italy
Catalytic decomposition of DCOOD studied by reactive scattering of a modulated DCOOD nozzle beam by a polycrystalline platinum surface in ultra high vacuum.	Friedrich Steinbach; Volker Hausen Institut für Physikalische Chemie der Universität, Hamburg
Effect of vibrational wall accommodation on small signal gain in CO_2-N_2-H_2O gas-dynamic laser.	N.K. Mitra DFVLR Cologne, W. Germany, and M. Fiebig Gesamthochschule Duisburg, W. Germany
Transport coefficients and relaxation phenomena in vibrational non-equilibrium gases.	Bernard Zappoli Société Européenne de propulsion, BP 802, 27200 Vernon, France
Shock wave structure in water vapour.	R. Synotzik; W. Garen; A. Frohn; G. Wortberg Institut für Allgemeine Mechanik, Technische Hochschule, 5100 Aachen, Germany
Tangential momentum accommodation coefficients of rare gases on poly-crystalline metal surfaces.	R.G. Lord Department of Engineering Science, *Oxford University*, UK
A new apparatus for gas surface inter-action studies.	M. de Paz; C. Maccio; F. Tommasini; V. Valbusa Gruppo Nazionale Strutture della Materia del CNR Istituto di Scienze Fisiche, Genova, Italy
Investigations on the interaction of gases and well-defined solid surface with respect to reduction of aerodynamic friction and aerothermal heating.	E. Steinheil; W. Scherber; M. Seidl; H. Rieger Dornier System GmbH, Friedrichshafen, W. Germany
The production of helium nozzle beams with very high speed ratios.	G. Brusdeylins; H-D. Meyer; J.P. Toennies; K. Winkelmann Max-Planck-Institut für Strömungs-forschung, Göttingen, W. Germany
Nozzle beams with extremely narrow velocity spreads extracted from pure or seeded light gas (He, Hz) free jets over-expanded in relatively high pressure environments.	R. Campargue; A. Lebéhol; J.C. Lemonnier Centra d'Etudes Nucléaires de Saclay, BP 2, 91190 Gif-sur-Yvette, France

Title	Author, etc
Monte Carlo calculations of the axi-symmetric rarefied transition flow past a bluff faced cylinder.	D.I. Pullin University of Melbourne, Parkville, Australia, and J. Davis; J.K. Harvey Imperial College, London, UK
Further results on the heat transfer to hemisphere-cylinders and bluff cylinders between continuum and free molecular flow limits.	G.T. Coleman; S.C. Metcalf; C.J. Berry RAE Farnborough, Hants, UK
Formation and detection of high-energy cluster beams.	O.F. Hagena; W. Henkes Kernforschungszentrumg Karlsruhe, Institut für Kernverfahrenstechnik, 7500 Karlsruhe, Germany (FR), and U. Pfeiffer Institut für Aerobiologie der Fraunhofergeseellschaft, 5949 Grafschaft, Germany (FR)
The transmission probability of free molecular flow through a tube.	Robert J. Cole Department of Mathematics, University of Strathclyde, Glasgow, UK
The conductance of very long inclined tubes in collisionless flow with a mean speed.	D.C. Pack; K. Yamamoto Department of Mathematics, University of Strathclyde, Glasgow, UK
Monte Carlo simulation of nozzle beam expansions.	Ashok V. Chatwani Max-Planck-Institut für Strömungsforschung, Göttingen, W. Germany
Theory and experiments on gas kinetics in evaporation.	Tor Yrrehus The Norwegian Institute of Technology, Trondheim, and John F. Wendt Von Karman Institute for Fluid Dynamics, Belgium
Quasisteady solution for the one-dimensional evaporation problem using entropy-balance relation.	T. Soga Institut für Luft- und Raumfahrt, RWTH Aachen, W. Germany
The elastic scattering of helium from (100) copper.	J. Lapujoulade; G. Armand; Y. Lejay Service de Physique Atomique Section d'Etudes des Interactions Gaz-Solides, CEN, Saclay, BP 2, 91190-Gif-sur-Yvette, France

Title	Author, etc
The visco-magnetic heat flux: an experimental study in the Burnett regime.	L.J.F. Hermans; G.E.J. Eggermont; P.W. Hermans; J.J.M. Beenakker Huggens Laboratorium, Rijksuniversiteit Leiden, The Netherlands
Inlet flow with slip.	B. Gampert Universität Essen - Gesamthochschule, Essen, Germany
Couette flow problem for a gas with discrete velocity distribution.	H. Cabannes Université Pierre et Marie Curie, Paris, France
Dissociation within the shock-front.	Helmut H. Peller; Franz J. Hindelang Fachbereich Luft- und Raumfahrttechnik, Hochschule der Bundeswehr, München, W. Germany
Experimental investigation of the structure of weak shock waves in noble gases.	W. Garen; R. Synofzik; A. Frohn; G. Wortberg Institut für Allgemeine Mechanik, Technische Hochschule, 5100 Aachen, Germany
Argon clusters in a supersonic beam: size, temperature and mass fraction of condensate, in the range 40 to 1000 atoms per cluster.	J. Farges; M.F. de Feraudy; B. Raoult; G. Torchet Groupe des Agrégats Moleculaires, Laboratoire de Diffraction Electronique, Université de Paris, Sud 91405 Orsay, France
Isotope effect on the formation of hydrogen cluster beams.	W. Obert Kernforschungszentrum Karlsruhe, Postfach 3640, 7500 Karlsruhe, Germany (FR)
Dimers in free jets and their total collision cross section.	A. van Deursen; J. Reuss; S. Stolte Katholieke Universiteit, Fysisch Laboratorium, Toernooiveld, Nijmegen, The Netherlands
Mass dependent molecular beam focussing by cross-jet deflection.	J. Gspann; H. Vollmar Institut für Kernverfahrenstechnik, Universität and Kernforschungszentrum, 7500 Karlsruhe, Germany
Heat transfer in binary mixtures of monatomic gases for high temperature differences and for a large Knudsen number range.	Dieter Braun; Arnold Frohn Institut für Allgemeine Mechanik der RWTH Aachen, 5100 Aachen, Germany Institut für thermodynamik der Luft- und Raumfahrt, Universität Stuttgart, 7000 Stuttgart, Germany

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Title	Author, etc
Drag reduction of a sharp flat plate located in a hypersonic flow with large valves of the rarefaction parameter V by means of a 'fore-leading edge'.	C. Bisch Laboratoire d'Aérothermique du CNRS, F-92190 Meudon, France
Flat plate skin friction in the range between hypersonic continuum and free molecular flow.	R.-D. Boettcher; G. Koppenwallner; H. Legge DFVLR Institut für Dynamik Verdünnter Gase Bunsenstrasse 10, 3400 Göttingen, W. Germany
Comparison of the direct simulated method with experiment for rarefied flat plate flow.	J. Davis; J.K. Harvey Department of Aeronautics, Imperial College, London, UK
Some general remarks on gas-surface scattering and rigorous evaluation of the scattering kernel for a simple model mechanism.	K. Bärwinkel Universität Osnabruck, Postfach 4469, D4500 Osnabruck, FRG
Non-Maxwellian velocity distributions in supersonic expansions of argon.	A.H.M. Habets; H.C.W. Beijerinck; N.F. Verster; J.P.L.M.N. de Warrimont Physics Department, Eindhoven University of Technology, Eindhoven, The Netherlands
The parallel speed ratio of a supersonic argon nozzle beam.	A.H.M. Habets; N.F. Verster; J.P.L.M.N. de Warrimont; H.C.W. Beijerinck Physics Department, Eindhoven University of Technology, Eindhoven, The Netherlands
Backswept plate in hypersonic flow.	Farouk Bachour; Manfred Becker DFVLR Institut für Angewandte Gasdynamik, 5000 Koeln 90, Germany (FR)
Drag and heat transfer measurements of cones at different wall temperatures in the transition and free molecule flow regime.	H. Legge DFVLR Institut für Dynamik Verdünnter Gase Bunsenstrasse 10, 3400 Göttingen W. Germany
Investigation of shock-shock interaction in hypersonic flow.	Gustav Schweiger; Manfred Becker DFVLR Institut für Angewandte Gasdynamik, 5000 Koeln 90, Germany (FR)
Interaction of underexpanded jets with adjacent flat plates.	J.C. Lengrand; J. Allègre; M. Raffin Laboratoire d'Aérothermique du CNRS, F-92190 Meudon, France

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A local Green's function method for the numerical solution of the Boltzmann equation.	J. Dorning; C. Pescatore; G. Spiga Laboratorio di Ingegneria Nucleare dell'Università di Bologna, Bologna, Italy
Knudsen layers: some problems and a solution technique.	Carlo Cercignani Istituto di Matematica, Politecnico di Milano, Milano, Italy
Rarefied gas dynamics of the separation nozzle - an aerodynamic device for the large-scale enrichment of uranium.	E.W. Becker; P. Bley; U. Ehrfeld; W. Ehrfeld Kernforschungszentrum Karlsruhe, Institut für Kernverfahrenstechnik, Postfach 3640, 7500 Karlsruhe, Germany (FR)
Velocity determination in an expansion flow of gases and gas mixtures in a free jet.	K.A. Bütefisch DFVLR Institut für Dynamik Verdünnter Gase Bunsenstrasse 10, 3400 Göttingen, W. Germany
Influence of electron beam-body interactions on vibrational temperature measurements.	Knut Krhardt; Gustav Schweiger DFVLR Institut für Angewandte Gasdynamik, 5000 Koeln 90, Germany (FR)
Isotope separation near a sphere and a cylinder in nearly-free molecular flow.	P. Louvet Division de la Chimie, CEN Saclay, 91190 Gif-sur-Yvette, France
Analysis of the time-evolution of a multi droplet system in the kinetic theory of condensation-vaporization.	N. Bellomo; R. Lolodice; G. Pistone Politecnico of Torino, Italy

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Appendix B

LIST OF ABBREVIATIONS OF RESEARCH CENTRES

ALU	Institüt für Angewandte Mathematik der Albert-Ludwigs-Universität D7800 Freiburg Hebelstr 40 W Germany
ARA	Aircraft Research Association Ltd Manton Lane Bedford England
CENS	Centre d'Etudes Nucléaires de Saclay Service de Chimie Physique BP No.2 91190 Gif-sur-Yvette France
CERT	Centre d'Etudes et de Recherches de Toulouse 2 Avenue Edouard Belin 31055 Toulouse-Cedex France
CIT	Aerodynamic Department Cranfield Institute of Technology Cranfield Bedford England
CNRS	Centre National de la Recherche Scientifique Laboratoire d'Aerothermique 4 Route des Gardes 92 Meudon France
DFVLR (D)	Deutsche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt Institüt für Dynamik verdünnter Gase 34 Göttingen W Germany
DFVLR (G)	Deutsche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt Aerodynamische Versuchsanstalt Göttingen 34 Göttingen Bunsenstrasse 10 W Germany
DFVLR (PWG)	Deutsche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt Institüt für Angewandte Gasdynamik 505 Porz-Wahn Linder Höhe W Germany

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DFVLR (PWL)	Deutsche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt Institüt für Luftstrahlantriebe 505 Porz-Wahn Linder Höhe W Germany
DFVLR (S)	Deutsche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt Institüt für Plasmadynamik 7 Stuttgart-Vaihingen Allmandstrasse 124 W Germany
DFVLR (SR)	Deutsche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt (D7) Stuttgart-Vaihingen Pfaffenwaldring W Germany
EMI	Ernst Mach Institüt 78 Freiburg/BR Eckerstrasse 4 W Germany
ENSMA	Laboratoire d'Energetique et de Thermique Rue Guillame VII 86 Poitiers France
ERNO	ERNO - Bremen Ramfahrttechnik Hunefeldstrasse (D28) Bremen W Germany
EUT	Fluid Dynamics Laboratory Physics Department Eindhoven University of Technology Postbox 513 Eindhoven The Netherlands
FDS	Firma Dornier System 7990 Friedrichshofen Postfach 648 W Germany
FFA	The Aeronautical Research Institute of Sweden PO Box 11021 S.161 11 Bromma 11 Sweden
GFW	Gesellschaft für Weltraumforschung mbH 53 Bonn-Bad Godesberg 1 Kölnerstrasse 171 Postfach 410 W Germany

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GHDF	Gesamchochschule Deusburg Institüt für Fluiddynamik Bismarckstr 81 (D4) 100 Duisburg W Germany
HBN	Hochschule der Bundeswehr FB Luft-v Raumfahrt-technik 8014 Neubiberg Fliegerhorst Geb 25
ICL	Imperial College of Science and Technology Department of Aeronautics Prince Consort Road Kensington London SW7 2BY
IKK	Kernforschungszentrum Karlsruhe Institüt für Kernverfahrenstecknik 75 Karlsruhe 1 Postfach 3640 Germany
ILR	Institüt für Luft-und Raumfahrt Technische Universität Berlin 1 Berlin 10 Marchstrasse 14 W Germany
IMPU	Istituto di Matematica Politecnico di Milano Piazza Leonardo da Vinci 20133 Milano Italy
IMR	School of Aerospace Engineering Istituto di Meccanica Razionale Politechnico di Torino Corso D.olegli Abuzzi 24 10129 Torino Italy
IMUT	Instituut for Mekanikk Universitetet i Trondheim 7034 Trondheim - NTH Norway
IPC	Universität Göttingen Institüt für Phys. Chemie Burgerstrasse 50 (D34) Göttingen
ISL	Institüt Franco-Allemand de Recherches de St Louis/Deutsch Französisches Forschungsinstitüt St Louis 12 Rue de l'Industrie 68 Saint Louis France

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ITFB	Institüt für Thermo-und Fluiddynamic Technische Universität Berlin 1 Berlin 12 Strasse des 17 Juni 135 W Germany
ITFBQ	Instutüt für Thermo-und Fluiddynamic der Ruhr-Universität Bochum 463 Bochum - Querenburg Postfach 2148 W Germany
ITS	Department of Aeronautics Institute of Technology 10044 Stockholm 70 Sweden
LDSR	Université de Provence Centre St Jérome Laboratoire de Dynamique des Systèmes Réactifs Traverse de la Barasse 13 Marseille 13^{e} France
LRBA	Direction Technique des Engins Laboratoire de Recherches Balistiques et Aerodynamiques de Vernon 27 Vernon France
MBB	Messerschmitt-Bolkow-Blohm GmbH 8 München 25 Postfach 549 W Germany
MPIS	Max-Planck-Institüt für Strömungsforschung 3400 Göttingen W Germany
NLR	Nationaal Lucht-en Ruimtevaartlaboratorium Sloterweg 145 Amsterdam (17) Netherlands
ONERA	Office National d'Etudes et de Recherches Aerospatiales 29 Avenue de la Division Leclerc 92 Chatillon-sous-Bagneux France
OXU	University of Oxford Department of Engineering Science Parks Road Oxford OX1 3PJ England

PTMR	Politecnico di Torino Instituto di Meccanica Razionale Corso Duca Degli Abruzzi 24 10129 Torino Italy
RAE (B)	Aerodynamics Department Royal Aircraft Establishment Bedford England
RAE (F)	Aerodynamics Department Royal Aircraft Establishment Farnborough Hampshire England
RWTH	Institüt für Thermodynamik RWTH Aachen D-5100 Aachen W Germany
Shell	Shell Research Ltd Thornton Research Centre Chester CH1 3SH England
THAD	Institüt für Aerodynamik Technische Hochschule Aachen D51 Aachen Templergraben 55 W Germany
THAM	Institüt für Allegemeine Mechanik Technische Hochschule Aachen 51 Aachen Templergraben 55 W Germany
THARL	Institüt für Luft-Raumfahrt Technische Hochschule Aachen 51 Aachen Templergraben 55 W Germany
THAS	Lehrstuhl für Strahlantriebe Technische Hockschule Aachen 51 Aachen Templergraben 55 W Germany
THD	Institüt für Mechanik Technische Hochschule Darmstadt 61 Darmstadt Arheilgerstrasse 1 Germany

TUBS	Institüt für Strömungsmechanik der Technischen Universität 33 Braunschweig Bienroder Weg 3 W Germany
TUD	Delft University of Technology Department of Aerospace Engineering Kluyverweg 1 Delft The Netherlands
TUKR	Technische Universität Karlsruhe Rechenzentrum 75 Karlsruhe Englerstrasse 2 W Germany
TUKS	Technische Universität Karlsruhe Institüt für Strömungslehre und Strömungsmaschinen 75 Karlsruhe Kaiserstrasse 12 W Germany
TUKT	Technische Universität Karlsruhe Institüt für Thermodynamik und Karltetechnik D7500 Karlsruhe W Germany
TUMF	Institüt für Flugantriebe Technische Universität München Gabelsbergerstr 137 D8000 München W Germany
TUMS	Institüt für Strömungsmechanik Technische Hochschule München 8 München Arcisstrasse 21 W Germany
TUSR	Institüt für Raumfahrtantriebe Technische Universität Stuttgart Pfaffenwald W Germany
TUTI	Universität Karlsruhe Thermodynamisches Institüt Kaiserstrasse 12 (D75) Karlsruhe 1 W Germany
UBAE	University of Bristol Department of Aeronautical Engineering Queen's Building University Walk Bristol BS8 1TR England

UCED	Cambridge University Engineering Department Trumpington Street Cambridge England
UEFM	Universität Essen Fachbereich Mechinentechnik 4300 Essen 1 Postfach 6843 W Germany
UGAFM	Glasgow University Department Aeronautics and Fluid Mechanics Glasgow W2 Scotland
ULC	The City University Department of Aeronautics St Johns Street London EC1 England
ULICME	Imperial College Department of Mechanical Engineering Exhibition Road London SW7 England
ULQMC	University of London Queen Mary College Department of Aeronautical Engineering Mile End Road London EQ England
ULUC	University of London University College Department of Mathematics Gower Street London WC1E 6BT England
UMMF	University of Manchester Department of Mechanics of Fluids Manchester M13 9PL England
UMIMF	Université d'Aix-Marseille Institüt de Mécanique des Fluides 1 rue Honnorat 13003 Marseille (Bouches-du-Rhône)
UNM	The University of Newcastle-upon-Tyne School of Mathematics Newcastle-upon-Tyne NE1 7RU England

UoSAA	University of Southampton Department of Aeronautics and Astronautics Southampton SO9 5NH England
UoSIT	University of Stuttgart Institüt für Thermodynamik der Luft-und Raumfahrt Pfaffenwaldring 31 (D7) Stuttgart 80 W Germany
UPaMT	Université de Paris VI Mécanique Théorique 9 Quai Saint Bernard 75 Paris 5^{e}
UPMC	Université P. et M. Curie Laboratoire de Mécanique Théorique Tour 66 4 Place Tussieu 75005 Paris France
UPoS	Laboratoire de Physique et Méchanique des Fluides Faculté des Sciences 40 Avenue du Recteur Pineau 86 Poitiers France
USaCC	Fluid Mechanics Computation Centre Department of Mathematics University of Salford Salford 5 Lancashire England
UShF	University of Sheffield Department of Fuel Technology and Chemical Engineering Mappin Street (St George's Square) Sheffield S1 3JD England
USM	University of Strathclyde Department of Mathematics Livingstone Tower 26 Richmond Street Glasgow G1 1XH England
VKI	Von Karman Institute for Fluid Dynamics 72 Chaussé de Waterloo 1640 Rhode-Saint-Genése Belgium

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UNCLASSIFIED

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17. Abstract

This Memorandum reviews the recently completed and current work programme on various aspects of hypersonic aerodynamics research being conducted in European research institutes. Three main areas have been covered, lifting bodies, propulsion aerodynamics, and real gas effects. In each of these sections all jobs have been listed in specialised sub-sections to form a rapidly addressed index. Additionally, there is a brief description or comment on each job, together with references to published papers etc, and an up-to-date address for each contributor.

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